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STRUCTURAL SURVEY OF THE ADIRONDACK ANORTHOSITE

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ABSTRACT

The mutual relations, shape, and origin of the Adirondack intrusives are discussed. Gabbro, anorthosite, and syenite series are considered closely related consanguineous members of a common parent magma. Frictional forces seem to have played a dominant rôle in the differentiation of the parent magma. Many of Bowen's views are confirmed by the field work, others have to be modified to meet the facts. The magma is believed to have risen from the southern edge of the Canadian Shield obliquely to the south.

GENERAL STATEMENT

In 1925 and 1926 the writer was engaged in mapping the Newcomb Quadrangle for the New York State Museum. In this work certain problems arose which called for a detailed structural survey of the interesting anorthosite mass which occurs within this quadrangle. Accordingly, the writer spent eight months in 1926, 1928, and 1929 studying the tectonics of this anorthosite and the belt of igneous rocks which surrounds it. This work has been carried out independently, and the present article is based on this later work only. The more detailed data upon which the following summary is based will be published soon. Discussion of the present paper should await the publication of the other article.

The writer feels greatly indebted to the geologists of the New York State Museum who have compiled the results of extraordinarily difficult field work in the bulletins and geological maps of the

Adirondacks. His thanks are due also to Drs. Esper S. Larsen and Tom Barth for the privilege of discussing with them many Adirondack problems in the field. For the conclusions and eventual errors of this paper the writer is alone responsible.

THE PROBLEMS

The central Adirondacks are composed of a large body of anorthosite of pre-Cambrian age. This is younger than the sediments of the Grenville formation which surround it—mostly marbles, diopside-quartzites, mixed gneisses, etc.—and within this border zone, but reaching far into the Grenville area, there appears a series of gneissoid syenitic and nordmarkitic rocks ("syenite series"). The syenite series includes some acid, granitic phases. Hundreds of small gabbro bodies outcrop both in the syenite belt and in the anorthosite.

For many decades, two problems have been outstanding in the Adirondack geology:

1. What is the relation between the anorthosite and the surrounding igneous rocks?

2. What is the shape of the intrusive masses?

A third problem was added in 1917 by N. L. Bowen:

3. Do the three principal igneous rocks, gabbro, anorthosite, syenite series, afford an example of crystal settling as a means of magmatic differentiation?[1]

1. RELATION BETWEEN THE ANORTHOSITE AND THE SURROUNDING IGNEOUS ROCKS

The writer considers anorthosite, gabbro, and syenite series closely related, consanguineous members of a common "parent magma." Within the now exposed level of the earth's crust, this parent magma has split into anorthosite, gabbro, and syenite series. The diversified phenomena of the splitting or differentiation are well exposed.

a) *Relation anorthosite-syenite series.*—Along contact zones of these two rocks, a complete gradation from anorthosite to syenite seems to be the rule. It is observed that the number of labradorite crystals of the anorthosite decreases steadily, and the proportion of a more acid plagioclase, together with some quartz, biotite, horn-

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXV (1917), pp. 209–43.

blende, augite, or garnet increases. Such transitional zones may be several thousand feet thick. In detail, the gradation consists of a sequence of subparallel layers, each one having an approximately constant composition. The layers never cut each other.

The intermediate zones have been termed "whiteface type anorthosite" or "border phase anorthosite." Although the general appearance and mineral composition of this rock may vary considerably, *it is always foliated*. The orientation of the flow-layers depends on local factors; in some exposures they lie approximately horizontal, in others they stand vertical, or they may have intermediate inclinations. One and the same layer may change its strike and dip, and the intensity of the foliation may increase and decrease.

There is another, rarer, type of contact between anorthosite and syenite in which the anorthosite remains massive, and is traversed by a multitude of irregularly oriented veins, dikelets, and stringers of a grayish white rock. These fade out into minute cracks, filled with quartz and garnet mainly; the broader portions are composed of an acid rock, intermediate between syenite and granite, and usually garnetiferous. Although mostly lenticular and blind, these acid veins increase in number and thickness toward adjacent syenite bodies, and some of them even lead into a syenitic rock which contains lumps and spheroids of anorthosite. The farther into the syenite one goes, the fewer are these fragments of anorthosite, until they cease entirely. It was such syenite dikelets in anorthosite which Cushing examined in 1900, and which led him to the conclusion that the syenite was "younger" than, and intrusive into, the anorthosite. Ever since, the Adirondack geologists have adopted this view, and the relationship between the two principal igneous rocks has been considered settled.

The writer, who has seen Cushing's type locality as well as many additional exposures of the same kind, cannot concur in his interpretation. One of the most important points is the fact that the great majority of the syenite veins occur in massive anorthosite and *avoid the foliated border phase*. The writer has discussed the significance of such a relation elsewhere.[1] Furthermore, the dikelets within the

[1] R. Balk, "Die primaere Struktur des Noritmassivs von Peekskill am Hudson etc.," *Neues Jahrbuch f. Mineralogie*, Beilage-Band LVII (1927), Abt. B., pp. 283–84.

massive anorthosite are strongly schistose and stretched, and the directions of deformation coincide with flow movements of the anorthosite, determined otherwise. Frequently, the veins pass into shear-zones or flexure-zones of the anorthosite; in some cases a vein is squeezed out here and reappears some distance away, the space in between being a shear-zone of anorthosite. Some dikelets were observed which carried labradorite phenocrysts, and others graded imperceptibly into anorthosite. Thus, a close relationship exists between the material and the flow movements of the anorthosite and syenite; both grade into one another.

The phenomena mentioned can be explained best if one considers the syenite to be in the nature of a "mother-liquor" which has been squeezed out from an increasingly inert and immobile crystal mush. Where the mother-liquor withdrew uniformly, and where the concentration in labradorite crystals increased uniformly, the transition between both rocks is a uniformly foliated zone. But where large crystal masses had already consolidated, while remnants of mother liquor still lingered between them, the syenitic juices seem to have been squeezed out, during a final stage, through narrow channels, jammed in between the clusters of solid crystals. Hence the dikelets are strongly deformed, and are absent from foliated anorthosite.

There are additional lines of evidence, not discussed here, which point definitely to the same relation between anorthosite and syenite.

b) *Relation anorthosite-gabbro.*—Gabbros are considered early segregations of basic minerals in the parent magma which has given rise to anorthosite and syenite.

Since gabbros in the Adirondacks have been described as distinctly younger than both anorthosite and syenite, the writer has studied their contact relations with special care. Out of some thirty gabbros, twenty-five grade marginally into anorthosite. The transitional zones may be a hundred feet wide or more, but may locally dwindle down to nothing. The anorthosite becomes foliated and more basic, developing the same kind of border phase as it does toward syenite. Hornblende and biotite are especially common. These two minerals, together with oligoclase-andesine, and occasionally some quartz and garnet, may form amphibolitic zones

around entire gabbro bodies. Toward the massive interior of the gabbro, hornblende grades into uralite and augite, biotite often forms little nodules, the plagioclase becomes labradorite, and hypersthene, ilmenite, and a little olivine appear.

The writer has failed to find inclusions of anorthosite in gabbro, or any other signs which might indicate intrusive relations between the two rocks. But single phenocrysts of labradorite, just like those of the anorthosite, were found in several gabbros.

Gabbro and anorthosite also grade into one another through a series of parallel layers. Although the directions of foliation within the gabbro may be irregular, and may differ from the surrounding border-phase anorthosite, the individual layers never cut each other. The foliated zone of a gabbro is always narrower than the rim of foliated anorthosite, and where the whole transitional zone has been locally sheared off, massive gabbro lies directly against nearly (but never quite) massive anorthosite. Such exposures have probably suggested a younger age of the gabbros.

c) *Relation gabbro-syenite series.*—Gabbros within syenite, which the writer has been able to examine, are also segregations of basic minerals, of the same type and appearance as those gabbros which appear in the anorthosite.

Gradational contact zones, with foliated syenite on one side and foliated gabbro on the other, are well exposed, for instance, on the southeastern slope of Clements Mountain (Lake Placid-Ausable quadrangles). Gabbro was never seen intrusive in syenite layers. But pegmatitic dikes of syenite commonly cut across the gabbro layers. Pegmatitic, or even normal, syenite often cuts across whole gabbro bodies, splitting them into two. Basic pegmatitic dikes and veins are rare. One finds acid pegmatites with the same mineral combination as is characteristic of the syenite pegmatites. This relationship between gabbro and syenite is further indicated by the shape of the gabbro bodies (p. 294).

The writer has not had an opportunity to visit the gabbros which have been recently described by J. L. Gillson and others as younger than syenite.[1] If such gabbros actually exist, they are of no immediate importance in the present problems.

[1] J. L. Gillson; W. H. Callahan, and W. B. Millar, "The Age of Certain of the Adirondack Gabbros, etc.," *Jour. Geol.*, Vol. XXXVI (1928), pp. 149–64.

2. THE SHAPE OF THE INTRUSIVE BODIES

a) *The anorthosite.*—The Adirondack anorthosite is very probably of lenticular shape, tilted to the northeast at 20° to 30°, and with a longest horizontal axis running northwest—southeast. The maximum thickness is estimated at twelve miles, the minimum at less than ten miles.

In the north and south, the present land surface exposes the upper half of the lens, which is curved convexly outward. But in the east, the margin curves inward and downward, and the floor, consisting of Grenville sediments, is exposed in some places. The dip-angles range from 30° to 0°. In the west, unfortunately, exposures are poor; lakes, swamps, and sand flats cover large areas and conceal the details of the shape of the anorthosite. Owing to the marginal gradation of anorthosite into syenite, the determination of the true contact zone is often difficult.

b) *The syenite series.*—The syenitic rocks in the vicinity of the anorthosite do not form a massif of a definite shape. Extending outward from the central intrusive, they surround it as an extensive system of sills, inserted concordantly into Grenville strata. Most of the sills are tilted gently in a northerly direction. Some rest on sediments; others overlie the upper surface of the anorthosite and are covered by the sediments. Some appear within the foliated border of the anorthosite. There are sills which plunge under the anorthosite, merging and grading into the latter as mentioned in the foregoing.

Many sills have a lenticular shape, and several such units may coalesce, may grade here into anorthosite, may rest elsewhere on, or include fragments of, Grenville sediments; they may envelop gabbro bodies, and may pass into granitic rocks. The term "sill" is here used because the syenite bodies are always concordant with the foliation of the Granville strata and with the other foliated igneous rocks. Cross-cutting contacts on a large scale have never been observed.

c) *The gabbros.*—Out of fifty-one gabbro bodies studied by the writer, thirty-five have the shape of a ball or a spheroid or an egg. Some four or five in the vicinity of Willsboro and Mineville are flat, pancake-like. The typical appearance of a gabbro is a round body, resting on a saucer-shaped floor of strongly foliated anorthosite

(or syenite), about like an egg in a nest. The better the exposures, the more clearly is this relation shown (e.g., Peaked Hill, Paradox quadrangle; Clements Mountain and associated gabbros, Lake Placid-Ausable quadrangles; Iron Mountain and vicinity, Elizabethtown quadrangle). The upper cover of gabbros is usually eroded away, but in the Jay Mountains (Ausable quadrangle), the complete cross-section of one of the largest gabbros in the Adirondacks is exposed. It has the shape of a blunt torpedo, 2 miles long, and has been completely covered by border phase anorthosite. It is of especial interest that the foliation of the surrounding rock is most intense along the floor.

3. THE ORIGIN OF THE INTRUSIVE ROCKS

No matter how the magma has occupied its present place in the earth's crust—whether by stopping, or by crystal settling, or by pushing aside the wall rocks, by assimilation of the country rock, or by a combination of these methods—as long as it has left behind visible traces of its primary flow movements, the directions and channels of its advance can be determined as confidently as the motion of a glacier, mud flow, or lava flow can be recorded from their flow structures. Likewise, the mutual relations of the different igneous rocks can be accurately determined by a detailed study of their flowage.

One of these flow structures, the foliation, has long been recognized in the Adirondacks. Every quadrangle report and almost every other article describes and discusses at length this important structural feature. There are many additional traces of magmatic movements, as recognized and described in detail by H. Cloos.[1] The writer does not intend to outline in this abstract the methods applied.

Only a few geologists have systematically measured and mapped the flow structures in the Adirondacks, and one of the chief objects of the writer has been to fill in this gap. The survey is, of course, far from complete, but has been extended far enough to allow a satisfactory interpretation of the observed phenomena.

[1] H. Cloos, "Bau und Bewegungen der Gebirge in Nordamerika, Skandinavien und Mitteleuropa," Berlin, Gebr. Borntraeger (1928); H. and E. Cloos, "Die Quellkuppe des Drachenfels am Rhein," *Zeitschrift fuer Vulkanologie* (1927), p. 33; H. Cloos, "Tektonische Behandlung magmatischer Erscheinungen. I. Das Riesengebirge," Berlin, Gebr. Borntraeger (1925).

The exposed structural features point to the following process of emplacement and differentiation: A "parent magma" in which appreciable quantities of solid labradorite and also ferromagnesian minerals were already suspended has been intruded into the Grenville formation from the north and northeast—so to speak from "under the edge of the Canadian Shield"—obliquely upward to the south and southwest. The farther the magma advanced, the narrower grew the channels along which it moved, the greater became the effect of friction between the magma and the relatively stationary walls, as well as between the magma and its suspended crystals. The increasing friction must have retarded the motion of the suspended crystals; it has gradually crowded them together and reduced the mobility of these gathering crystal masses. The liquid portion of the parent magma ("syenite"), however, has continued to move on, probably as far as 10 or 20 miles into the Grenville strata, always conformable to gliding planes of the (partly liquefied) sediments.[1]

a) *The anorthosite.*—Because of the widening and coalescence of the originally narrow channels, due to the intrusion of additional magma, the arrested crystals have gradually united and formed a central body of labradorite. It has apparently grown under great pressure and little by little as new crystal residues were left behind by the passing parent magma. The crystals were predominantly labradorite (anorthosite), but there were also smaller quantities of ferromagnesian minerals (gabbro), and still smaller portions of mother-liquor, trapped here and there between the potentially solid blocks of crystals (local syenitic schlieren in anorthosite and gabbro). What is now a large body of anorthosite, covering some 1,200 square miles on the surface, seems to have been originally a much smaller cluster of labradorite which has gradually attained its present size owing to the constant addition of arrested crystals. The oldest part of the anorthosite lies in the southwest, and the youngest portions are in the northeast.

The advance of parent magma must have continued over an

[1] The intrusive activity has heated the Grenville formation to such an extent that the marble was rendered potentially liquid. It behaves locally like an intrusive rock, may cut across igneous rocks ("marble dikes"), and shows fantastic twisting and isoclinal contortions of its impure layers. This has been recognized and described by Ebenezer Emmons as early as 1842.

extremely long period of time. Passing through the space where the crystals were gathering, it seems to have pushed them about, stirred them up and disturbed them time and again, so that for a long time the clusters of crystals could not come to rest, although they have frozen into smaller blocks here and there.

This unique stage in the history of the anorthosite has left unmistakable traces: anorthosite is known as a thoroughly protoclastic rock in which practically every crystal of labradorite has its crushed border. In addition, many exposures display what might be termed a "block structure," in which the rock consists of a multitude of round or angular blocks, each one differing in color, proportion of labradorite phenocrysts, and mineral composition. There are almost always shear zones along the surfaces of these blocks of different composition, and it is a common thing to see blocks of anorthosite surrounded and included by anorthosite of slightly different color. These are features unknown from any other igneous rock, as far as the writer knows.

Apparently, mother-liquor and crystals separate owing to frictional forces. These forces are the stronger, the narrower the available channels and the larger the proportion of suspended crystals in the parent magma. The principle of "filter pressure" and "squeezing out," often advocated by Bowen, seems best to explain the observed phenomena, even though the mechanical problems implied by these terms lack, as yet, accurate experimental investigation.

b) *The gabbros.*—Initial stages in the history of this rock—gabbros *in statu nascendi*—are comparatively rare. In such cases, the surrounding anorthosite (or syenite) grows increasingly rich in biotite and hornblende. The foliated rock may have a small massive center, or a massive center may be altogether absent. *Such initial stages in the concentration of basic minerals are identical with normal basic flow layers.* Their shape is tabular or suggests a very flat lens. Thus, the gabbros appear to have originated through local accumulation of basic schlieren in the parent magma. With increasing size, their shape became spherical, the center grew massive, while hypersthene, augite, and olivine established themselves in the centers as more stable minerals than hornblende and biotite.

Some of the basic segregations existed before the mother-liquor

had withdrawn entirely from the labradorite masses. At any rate, the ball-shaped gabbros within the anorthosite have been potentially solid during a stage when there was enough interstitial liquid present in the crystal mush to make the mixture "flow" around the gabbro surface.

TEST FOR THE THEORY OF CRYSTAL SETTLING

Since the comagmatic relation between gabbros and anorthosite is certain, and since the floor of the anorthositic rocks is exposed in the field, a study of the gabbros is apt to throw light on the problem of crystal settling. According to this theory, heavy minerals should settle, in due time, to the bottom of a magma chamber, forming there something like a basal layer. The bottom of the anorthosite can be traced along the Lake Champlain shore for considerable distances between Port Douglas and Port Henry. It can be followed indirectly from Moriah southwestward for some 30 miles or more. *The gabbros show, indeed, a certain preference for this zone, although in a different way from that required by the theory.*

Instead of forming the largest bodies where the volume (cross-section) of anorthosite is largest, i.e., in the center and the western part of the massif, gabbros are totally absent there, a fact not mentioned in the literature. *All the gabbros are concentrated in the eastern third of the anorthosite, where its cross-section is narrowest.* Within this area, however, gabbros are fairly equally divided, and occur near the base of the anorthosite as well as near the top. Neither are those on the top less basic or less concentrated than those near the bottom of the anorthosite; nor is there a basal *layer* of gabbro. *The individual bodies all maintain the significant spherical shape and hardly ever touch each other.*

In spite of these facts, a tendency of the gabbros to settle with reference to the surrounding rock is clearly shown by the fact that all spherical gabbros are underlain by a layer of more or less schistose anorthosite, always curved concentrically downward. This synclinal, saucer-shaped floor is undoubtedly the result of a downward sagging of the gabbro; the movement of the great mass has strained and dragged downward the underlying material. To judge from the best instance of its kind, the Jay Mountain gabbro, the magma above a gabbro was not nearly so strongly compressed as the portions below. The writer thinks

that anorthosite or syenite above a gabbro may be practically massive, whereas the floor is strongly foliated.

Gabbros *in statu nascendi* do not have schistose floors, even if they are large. *This indicates that there is no tendency to settle downward, so long as the basic minerals are mixed up with parent magma. The tendency to settle becomes noticeable after the concentration of femic minerals reaches a certain stage, and after the resulting spherical body attains an appreciable size.*[1]

Gravity may play the predominant rôle in a laboratory test. But in the complex system of normal and rotational forces to which a moving magma of enormous size is subjected, gravity will be superseded, at least locally and temporarily, by other more powerful forces. The geologist who works in the field will often be satisfied if he finds evidence merely for the *tendency* of a rock to settle. The actual distribution of a rock may be widely different from what a laboratory experiment suggests, and yet the dynamic principle, as such, may be valid.

If the principle of crystal settling alone does not satisfactorily explain the distribution of the gabbros, which other factors interfere with it? Without going into details (which are here particularly complicated), it may be said that the concentration of gabbros in the east has probably something to do with the constricted and indented cross-section of the anorthosite, and also with the frequent interposition of Grenville xenoliths in this section of the massif.

From what has been said in the foregoing, the friction between mother-liquor and crystals must have been most intense where the passageway of the parent magma was constricted. Since the accumulation of basic minerals is greatly stimulated by this factor, the concentration of gabbros in this narrow zone of the magma chamber is not surprising.

Like most geological processes, the origin and distribution of the gabbros is due to a combination, co-operation, and interference of a

[1] These conditions are in harmony with Stoke's formula concerning the velocity of falling particles in liquids. According to this principle, scattered crystal grains are kept afloat, because the surface friction of each grain is greater than the gravitational force. The accumulation of basic minerals into a ball increases the radius of the "particle," while the surface friction—with reference to the volume and weight of the mass—decreases. This principle implies that large gabbros should settle faster than smaller ones.

number of independent factors: basic minerals in the parent magma are brought together through differential movement and friction in the melt. The basic constituents gather the faster, the narrower the local channel, and the more Grenville xenoliths are floating in the magma. As long as the femic minerals are mixed up with mother-liquor, their movements are not affected by gravity. The final concentration of the basic minerals, however, ejects the interstitial liquid; the specific gravity and the absolute weight of the cluster increases. Due to hydromechanical forces, the gabbros of this advanced stage take on a spherical or torpedo-like shape.

Through these changes, the balance between gravity, specific gravity of the gabbro, surface friction along its margin, effect of magmatic current, and many other factors, is also changed. The gravitational force gains in strength, and the gabbros above a certain size and concentration are forced to settle downward *with reference to the movement of the surrounding current* of mother-liquor. *The absolute movement is still obliquely upward, at least in many instances.*

The time factor is likewise of importance. If the magma had consolidated in an early stage, gabbros *in statu nascendi* would probably prevail. If more time was available, small spherical gabbros would be exposed, but probably without the schistose floors. If still more time is granted, large gabbros with schistose floors would prevail. An ultimate stage, not attained in the Adirondacks, might show the gabbros actually along the basal zone of the magma chamber. The whole process is slowed down still more by the retarding effect of the Grenville salients.

The complicated picture shows plainly that neither a laboratory test, where the conditions are purposely simplified, nor other theoretical considerations alone can predict just which combination of factors has prevailed in a given area. The course of events and the antagonism of the individual agencies, the "scale effect," can be learned only by a patient study in the field.

c) *The syenite series* plays the part of a mother-liquor. As such, it is by far the most generally "intrusive" rock, while it is extremely difficult to find apophyses or true dikes of anorthosite or gabbro. Wherever Grenville sediments are "soaked" or injected lit-par-lit, the intrusive component is syenite or granite, not gabbro or anortho-

site. Grenville inclusions in the Mount Marcy section of the anorthosite are not injected by the anorthosite. If several spherical gabbros lie close together, syenite will fill out the wedge-shaped spaces between them, the foliation bending conformably with the local gabbro surfaces. Where there are "dead" spaces, especially between indented contact planes of other rocks, syenite fills them out, often becoming pegmatitic, coarse-grained, and acid in composition.

The syenitic juices, escaping outward from the labradorite-filled central chamber, have dragged single labradorite crystals (not fragments of solid anorthosite!) for miles out into the belt of syenite sills. During a careful search on Arab Mountain, a syenite sill, 7 miles from the southwestern contact of the anorthosite, the writer was impressed by finding exactly three labradorite phenocrysts within some 2 square miles of good exposures of syenite.

From the preceding pages, it is obvious that the conception of a "cover" of syenite above the anorthosite (as required by the ideal process of crystal settling) is inadequate. Syenite sills do appear, of course, often in this position. But the floor of the intrusive is also followed by border phase, syenite and even granitic rocks, which underlie the anorthosite.[1]

A few remarks concerning the parent magma may close the article. Its existence is assumed because of the intimately consanguineous relations between the three principal igneous rocks. The question arises: What was the chemical composition of this parent magma, and are there exposures where parent magma may be seen?

Unfortunately, the field relations do not allow very accurate answers. As regards the chemical composition of the parent magma, one might think of estimating the approximate volume of anorthosite, gabbro, and syenite, and recalculating the sum-total. But the resulting rock would, in all probability, be too basic. It was stated

[1] The large syenite area which accompanies the southwestern contact of the anorthosite from Tahawus P.O. to Tupper Lake plays a peculiar rôle. In the north, it dips away from the anorthosite at angles from 80° to 55°. The dip becomes vertical farther south, until it turns over to the north. At the same time, the Grenville formation emerges, underlying the syenite from the south. Thus the syenite belt has the form of a wedge that rests in the south on Grenville sediments, and in the north on anorthosite into which it grades. The writer considers it something like a protective wall of mother-liquid in front of the differentiating parent magma.

in the foregoing that syenites frequently grade into normal gneissoid granites. *These granitic sills reach far into the Grenville areas, but beyond the reach of the syenites they are indistinguishable from the preanorthositic "Laurentian" granite.* Many observers have emphasized this fact. The amount of granitic mother-liquor genetically connected with the anorthosite remains unknown for the time being, but there are certain indications that a considerable portion of the Adirondack granites belong to the anorthosite rather than to the preanorthositic intrusions.

Although it is impossible to decide whether there are exposures of the true parent magma, it may be said that undifferentiated rocks appear along the eastern margin of the anorthosite. They contain labradorite phenocrysts, but otherwise seem to be nearly intermediate between syenite and gabbro.

Certain general problems, such as the depth of the intrusion, the thermal and dynamical conditions attendant to it, the deformation of the Grenville sediments, and many others, are not yet ready for discussion in this article.

THE MECHANICS OF FROST HEAVING

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ABSTRACT

The old theory that frost heaving is due to change in volume of water frozen was based on experiments with closed systems. Field observations and recent experiments indicate that soils, when subjected to freezing under normal conditions, usually behave as open systems. When the freezing of saturated soils results in little or no heaving, part of the water is forced through the soil voids below the zone of freezing, compressing or expelling air. Excessive heaving results when water is pulled through the soil to build up layers of segregated ice. These ice layers grow in thickness because water molecules are pulled into the thin film that separates the growing ice crystals from underlying soil particles. Since heavy surface loads may be heaved and much force is required to pull water through impervious clay, the water is put under high tension.

Heaving is limited by the tensile stress that may be developed in the water and by downward growth of ice crystals in soil voids. These two factors also probably explain the rhythmic banding due to alternating layers of ice and clay.

In well-consolidated clays the surface uplift equals the total thickness of the ice layers, the water content of the clay between the ice layers remaining approximately constant; but heaving is continuous and regular instead of intermittent. Clay is soft near the lowest ice layer because much of the water is unfrozen, the hardness increasing higher up where the temperature is lower and freezing has gone on for a longer time. Additional evidence has been obtained by freezing in open systems other liquids than water.

It has been generally assumed that frost heaving, as well as other pressure effects accompanying the freezing of water, is due to increase in volume of the water frozen. This assumption was based on experiments in which water was frozen in closed systems, i.e., systems from which the water present could not escape and into which additional water could not enter. The experiments of early investigators were limited to such systems.

In an investigation of frost heaving in 1914, the writer experimented with open systems on nights when the temperature was sufficiently low. The work was resumed in March, 1927, with an electric refrigerator, which made close control of temperature possible.[1]

Simple apparatus for freezing water in an open system is shown in Figure 1. A cylindrical container having a perforated bottom is

[1] The refrigerator was made available through the courtesy of the Frigidaire Corporation. Since November, 1927, the U.S. Bureau of Public Roads has given financial co-operation.

tightly packed with the soil to be tested, and is stood in a vessel containing sand, which can be kept saturated with water. This apparatus is placed in the bottom of the refrigerator and buried to the top in dry sand so that the soil is cooled from the top downward. A collar, fitting snugly around the container and resting on top of the vessel, prevents the entrance of dry sand. Container and vessel are held rigidly in place by a strong frame. A heavy lead disk resting on the soil in the container carries a recording pen which is in contact with a drum turned by a clock. This gives a graphic record of the amount and rate of movement of the soil surface during an experiment. Temperature is recorded on the same drum by another pen. Freezing extends gradually downward from the surface, and the interstitial spaces below the zone of freezing permit the movement of water either upward or downward according to the forces to which it may be subjected. This movement is without interference from outside forces, since air may readily enter the vessel, or be expelled, through the dry sand.

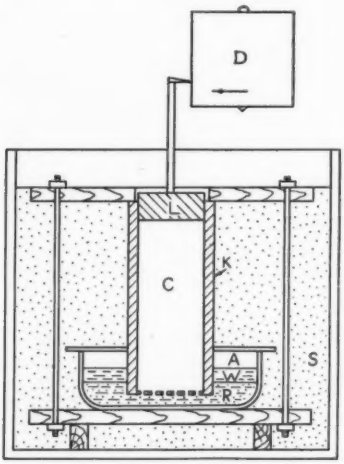

FIG. 1.—Apparatus for freezing soils in a system that is open with respect to water. *C*, soil; *K*, container; *A*, air; *W*, water; *R*, sand saturated with water; *S*, dry sand; *L*, lead disk with recording pen; and *D*, drum turned by a clock.

If a definite amount of water is cooled under atmospheric pressure, it freezes at 0° C., with an expansion in volume of about 10 per cent. Greater pressures tend to prevent solidification, because the distance between the water molecules increases when ice crystals form; therefore, with increasing pressure the freezing point is lowered. If the water is confined so as to prevent expansion, freezing results in high pressure; but the maximum pressure obtainable is 2,115 kilograms per square centimeter, for at this pressure and

$-22°$ C. ice III, which is denser than water, begins to form.[1] In such a system pressure develops because openings through which water can escape are absent.

In experiments with open systems, it was found that some soils, when kept saturated with water, freeze with no uplift of the surface, while others give uplifts ranging up to more than 60 per cent of the depth of freezing. An uplift of even 100 per cent was obtained in some tests through the formation of a layer of ice at the surface. When no heaving occurs, some of the water must be pushed downward by the growing ice crystals and expelled from the soil container; when the surface uplift is in excess of that which could result from the expansion in volume of the water frozen, it is obvious that additional water must have entered the container as a result of the freezing.

When liquids that solidify with decrease in volume are substituted for water in freezing experiments, similar pressure effects are obtained in open systems, although these liquids could develop no pressure as a result of freezing in closed systems.

Numerous observations made out of doors indicate that soils, when subjected to freezing under normal conditions, usually behave as open systems rather than closed systems. Frost heaving is often too great to be explained by change in volume of water present in the voids, and in other instances it is too little. Assuming the water content of soil to be 50 per cent—and it is usually much less—the change in volume, if all of it froze *in situ*, could account for an uplift of 5 per cent of the depth of freezing. The depth of freezing in the northern part of the United States seldom exceeds 2 or 3 feet; but a surface heaving of 6 inches is not uncommon, and an uplift of "a couple of feet" has been reported from Minnesota. On the other hand, the freezing of saturated soils is accompanied in many places by no appreciable uplift.

The entrance of additional water where soil heaving is excessive, and the partial expulsion of water from the soil voids where freezing results in little or no heaving, may be compensated for, in the one case, by the expansion and, in the other, by the compression of imprisoned air, or by the entrance and expulsion of air through pores

[1] P. W. Brigman, *Proc. Amer. Acad.*, Vol. XLVII (1912), pp. 441–558.

and cracks. Most soils probably contain sufficient air to permit the free movement of water during freezing.

Soil may behave as a closed system with respect to water when the water-table is flat over large areas and practically coincides with the surface so as to exclude air; but even under these conditions, lenses and layers of segregated ice can form if the soil texture is favorable, and differential heaving may be produced if there is sufficient variation in the conductivity of soil cover so that freezing does not begin everywhere at the same time. The distinction between closed and open systems in the ground is not sharply defined. As the resistance to the movement of ground water increases, an open system tends to grade into a closed system.

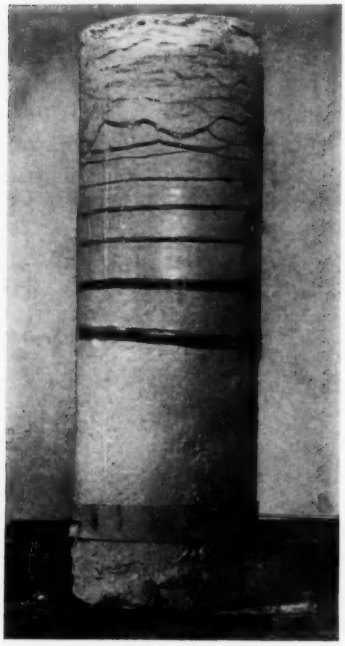

FIG. 2.—Cylinder of frozen clay. The surface uplift equals the total thickness of the ice layers. Scale in centimeters.

In laboratory experiments excessive heaving is always accompanied by the introduction of additional water and its segregation to form layers or masses of more or less pure ice (see Fig. 2). Similar layers of segregated ice have been formed in the ground where excessive heaving has been observed. An excellent illustration of such ice layers (see Fig. 3) was sent to me by Mr. F. C. Lang, of the Minnesota Department of Highways. The lump of clay shown in the photograph was excavated in the spring of 1929 from a street where the heaving was "a couple of feet." It is obvious that these ice layers could not have been formed by the freezing of water *in situ*.

An investigation of the factors involved in segregation and exces-

sive heaving has been made.[1] The chief factors are: size and shape of soil particle, amount of water available, size and percentage of voids, rate of cooling, and the surface load or resistance to heaving. Segregation occurs readily if the particle diameter is less than a micron, and under favorable conditions if the particles are slightly larger. Tabular particles, such as are found in clay, probably give results

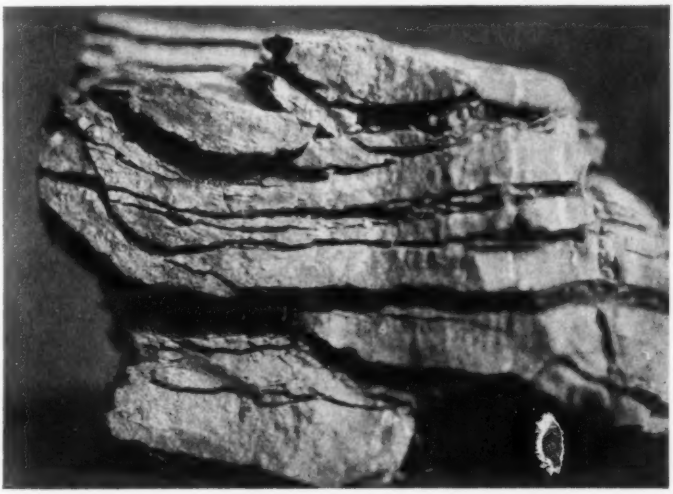

FIG. 3.—Clay containing ice layers from under a badly heaved street in St. Peter, Minnesota.

similar to those obtained with somewhat smaller particles that are more nearly isodiametric. Water occupying very small voids in soil does not freeze readily and may be undercooled in the immediate vicinity of ice crystals. The water remaining unfrozen at low temperatures is probably adsorbed water. Rapid cooling, when the temperature is near the freezing-point, prevents segregation in some soils but has little effect if the soil particles are sufficiently small and the other factors favorable. Moderate loads have less influence on the heaving of clay than the heat conductivity of the material used in applying the pressure; heavier loads tend to reduce heaving, but in

[1] Stephen Taber, "Frost Heaving," *Jour. Geol.*, Vol. XXXVII (1929), pp. 428–61.

laboratory tests with pure clay, surface loads of nearly 15 kilograms per square centimeter were required to prevent heaving. Moderate loads prevent the heaving of relatively coarse material.

It is commonly stated that frost heaving is upward because of less resistance to expansion in that direction, but this hypothesis is not supported by the facts. Experiments prove that the pressure effects accompanying freezing are due to the growth of ice crystals. The pressure is developed only in the direction of crystal growth, which is determined chiefly by the direction of heat conduction and the availability of water. Differential pressure is a minor factor, of little importance when soils freeze under normal conditions.

A tentative hypothesis has been advanced to explain the mechanics of the process by which ice crystals growing in open systems are able to exert pressure and overcome resistance.[1] A continuation of the investigation has led to the discovery of additional facts which shed more light on the problem.

A growing ice crystal is in contact with a thin film of water similar to the adsorbed layer which forms on many other solids that are in contact with water. As a molecule in the film is oriented and attached to the crystal, it is replaced by another from the adjacent liquid, thus maintaining the integrity of the film. If resistance to growth is offered by a solid body such as a soil particle, the pressure is exerted through the thin film of water that separates them. This film may consist of a single layer of molecules; but I am inclined to think that it is somewhat thicker, for the molecules in it possess considerable mobility. A unimolecular layer could not be expelled by pressure alone; thicker layers could be reduced through expulsion of some of the molecules under pressure, though this is probably resisted by the strong attractive forces. After the available water has been exhausted, the film may be frozen; but it does not freeze readily.

The orientation and attachment of a molecule to the crystal is accompanied by a slight repulsion, proportional to the change in volume; but this cannot be considered an essential factor in the process, for liquids that freeze with decrease in volume give pressure effects in open systems similar to those obtained with water.

[1] *Ibid.*, pp. 458–60.

Cohesion is greater between the molecules in the film and between these molecules and the ice, than it is between water molecules that are not similarly located close to ice crystals. Since no outside force is competent to push molecules of water into the film between the growing ice crystal and the resisting solid, the crystal must be displaced relative to the adjacent solid because water is pulled in between them; and this is made possible by the high intermolecular attraction, which prevents the separation of the water molecules.

During the growth of an ice layer in soils, water is pulled up through the interstitial capillary passages; but the upward flow cannot be attributed to capillarity, for there is no free surface or meniscus. Since ice crystals growing in an open system are able to overcome a resistance many times as great as atmospheric pressure, the water, in such cases, is actually pulled into the nourishing film under high tension.

The ultimate tensile strength of water has been estimated, from the energy required to separate the molecules when it is converted into gas, as over 1,300 atmospheres. A water column of large cross-section is placed under tension with difficulty, for the water is superheated when under negative pressure, even at temperatures below 0° C., and the formation of a gas phase immediately breaks the column. Extremely slender columns, or filaments, and thin films are more easily maintained under tension than larger ones; and this is the form in which water is present in clays.

Only rough estimates can be made of the maximum tensional stress developed in water during the freezing of soil. The surface load lifted can be measured in laboratory experiments; but to this it is necessary to add the frictional resistance of the frozen soil in contact with the container, the force necessary to separate the clay cylinder, and the force required to pull water through impervious clay to the growing ice crystals. Moreover, an ice layer must begin to form at some favorable point and then spread outward rather than form across the entire cross-section of the cylinder instantaneously.

Since the ratio of surface uplift to depth of freezing varies greatly with different soils under similar conditions of saturation, and with the same soils under different conditions of loading, the tensile stress that can be developed in the water is not the only factor limiting soil

heaving. If tensile strength were the only factor, the amount of uplift would equal the depth of freezing or be zero. The principal additional factors are the rate of freezing and the downward growth of ice crystals due to the freezing of interstitial water *in situ*. The gradual formation of ice in the soil voids below a growing ice layer probably explains the rhythmic banding due to development of successive ice layers as freezing extends downward in clays (see Figs. 2, 3, and 4).

FIG. 4.—Clay frozen under pressure of 15 kilograms per square centimeter. Ice is clear and sharply separated from clay.

In indurated clay, or in clay that has been thoroughly consolidated artificially, the layers of segregated ice are clear, for the most part, and very sharply separated from the frozen clay. The total thickness of these layers, as close as can be measured, is the same as the amount of surface uplift. The ice layers, because of slower cooling, tend to become thicker and more widely spaced with distance from the cooling surface. In unconsolidated clay the ice layers are not so sharply defined, and it is not usually possible to estimate accurately the thickness of the segregated ice. In tests with open systems where water can enter, moisture determinations show that the frozen clay between the ice layers contains the same percentage of water as clay below the depth of freezing. This observation confirms the conclusion that heaving in these tests is due to the formation of the ice layers and that the freezing of interstitial water causes practically no uplift. However, in spite of this, the rate of heaving, as shown by repeated experiments, is continuous under constant temperature, and never intermittent.

Using the apparatus shown in Figure 1, tests were made on indurated clay cut in the form of smooth, true cylinders and set in paraffin so as to equalize friction on all sides, and thus, as far as possible, prevent development of irregular ice layers. Temperature and heaving graphs for one of these tests, redrawn so that they start from the same vertical axis, are shown in Figure 5; and the distribution of the ice layers at the close of the experiment is shown in Figure 2. A sample of clay taken just below the frozen material and three samples taken between successive ice layers gave 22.0, 22.1, 21.8, and 22.0 per cent water respectively. When tested with the point of a knife,

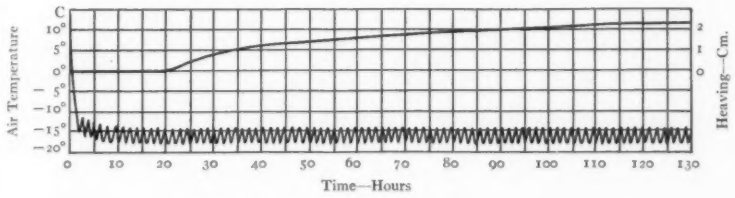

FIG. 5.—Graphs showing air temperature and rate of heaving during the freezing of the clay cylinder shown in Figure 2.

the clay between the lowest ice layers was found to be soft, as compared with that higher up, the hardness tending to increase toward the surface where the temperature was lower and freezing had gone on for a longer time.

The hypothesis which best explains the facts here outlined is that during the growth of an ice layer the voids in the adjacent underlying clay, beginning with the larger ones, tend to fill gradually with ice and thus increase the work that must be performed in supplying water to the ice layer. When resistance becomes too great, the flow of water to this ice layer stops and a new layer of ice begins to form near the bottom of the zone of frost penetration. More of the water in the clay between the ice layers freezes as the temperature gradually becomes lower, some of it possibly migrating to the ice layers; but previous tests with this clay have shown that 6 parts of water per 100 parts of dry clay do not freeze on prolonged exposure to low temperatures.

An ice prism in one of the layers continues to grow at the base

where it is exerting pressure against an adjacent soil particle as long as water molecules can enter the separating film and be attached to the crystal. If the soil particle is very small, the molecules travel only a short distance through the film to reach the points where they are attached. If the soil particle is larger, it takes longer for the molecules to reach their points of attachment; and meanwhile freezing may extend downward around the particle so as to gradually inclose it in ice. As soon as crystal growth is checked at any point, the temperature of the adjacent soil particle begins to fall, for heat is no longer liberated at this point by the conversion of water into ice; and, since water is a poorer conductor of heat and has a higher specific heat than the minerals present in soils, the temperature of the bottom of the soil particle will reach the freezing point sooner than the water with which it is in contact. This helps to bring about the inclusion of the soil particle in the ice. The formation of layers of segregated ice is possible only when the soil particles are excluded by the growing crystals, a process which is aided by slow freezing, for then the molecules have more time in which to penetrate between crystal and soil particle.

In carefully sized material having a particle diameter of about 2 microns, segregated ice forms under conditions of slow freezing, but not when freezing is rapid. Even with slow freezing segregation may be prevented by applying a little pressure to the surface. As the diameter of the soil particles diminishes, higher pressures are required to prevent heaving. The effect of pressure in reducing and preventing heaving in open systems seems to be due in part to a decrease in the mobility of molecules in films that are under pressure.

If heat is conducted upward from the bottom of a growing ice layer just fast enough to remove both the heat set free when water is converted into ice and the heat brought up by the water, the ice layer will continue to grow in thickness; but if heat is conducted away more rapidly, the freezing isotherm will move gradually downward, causing ice to form in soil voids below. As freezing extends downward in clay, cooling is slower and there is less resistance to the upward movement of water; therefore, the ice layers tend to become thicker. Conditions most favorable for slow freezing are a relatively

steep temperature gradient below the freezing-isotherm and a relatively gentle temperature gradient above.

Separation of the air dissolved in water, as freezing progresses, is a factor in interrupting the supply of water to the growing ice layers, but it is of relatively little importance. Examination of the ice with a strong magnifying glass shows that it contains small filiform cavities filled with air and oriented in the direction of crystal growth. These cavities, together with the parallel orientation of the ice prisms, give the ice a satiny luster. The cavities begin a short distance below the top of an ice layer and become more numerous lower down, but there is no difference in their abundance between the central and lower portions of thick ice layers. When boiled distilled water is used, with protective oil layers to prevent the absorption of air, the results obtained on freezing are not appreciably different. Also, when liquids which do not absorb air are substituted for water in freezing experiments, the same rhythmic banding occurs.

In order to prove that the pressure developed through the growth of ice crystals in an open system is limited by the failure of the water supply, and not by inability of the crystals to grow under greater pressure, the following experiment was performed.

The upper part of a strong fiber container, water-proofed with paraffin, was filled with clay and the lower part with water, the two being separated by a perforated disk of hard rubber with filter paper resting on top. The disk was held in place by a stiff steel spring that rested on the bottom of the container. Before filling the lower part of the container with water, air was removed from the clay by displacement with water and the clay thoroughly compacted for several days under a pressure of 14 kilograms per square centimeter. After introducing the water, the lower part of the container was stood in a can of impervious cement, and the upper part was strengthened by surrounding it with wood strips held in place by steel bands.

The container was placed in the refrigerator and buried to the top in dry sand. With the apparatus set up as described, and with the clay placed under a pressure of 14 kilograms per square centimeter by means of a piston inserted in the top of the container, the water in the lower part, because of the supporting action of the spring, was under a pressure of only about 10 kilograms per square centimeter.

As freezing progressed, the pressure on the clay increased; and at the close of the experiment it was about 15 kilograms per square centimeter.

The walls of the container were sawed through and one-half was removed to expose the cylinder of frozen clay (see Fig. 4). The rubber disk in the photograph is slightly displaced. The total thickness of the ice layers was between 2 and 3 centimeters, whereas almost no heaving could be obtained in experiments with this clay under similar pressures but with the water under no outside pressure. The spring in the reservoir was completely compressed, for the water had been pulled into the clay to build up ice layers in spite of the high pressure on the clay.

There is some evidence that rupturing of the upward-moving filaments and films of water under tension is one way by which water supply is interrupted and growth of ice layers stopped. The inability of molecules to enter films that are under pressure, or to enter fast enough to prevent the downward freezing of interstitial water, is probably another way in which the growth of ice layers is stopped. The data now available are insufficient to determine which of these methods is the more important.

When water is under tension because of the growth of an ice layer in clay, the stress is ordinarily greatest right at the points where water molecules are being pulled into the film which separates the growing ice crystals from the clay below, and it is therefore at this place that any break would occur. The breaking of a water filament, or film which is being drawn toward the ice layer, means that the molecules are separated beyond their range of attraction; or, in other words, a gas phase is formed between the liquid water and the ice. The gas phase, however, could not extend far below the ice layer, for the tensile stress in water a little below the ice is due to frictional resistance to the passage of the water through the small soil voids, and this stops as soon as the upward movement is checked.

On feeezing clays that are extremely impermeable because of high colloid content and that contain a high percentage of water, tensional cracks of polygonal pattern develop and extend downward in advance of freezing. As freezing progresses, the cracks are gradually filled with ice.[1] These results were obtained with South Carolina

[1] *Ibid.*, pp. 457–58.

Cretaceous white clay to which from 5 to 95 per cent bentonite had been added.

The hypothesis that the growth of ice crystals stops because of interruption of the water supply by the formation of a gas phase receives some support from freezing experiments with open systems in which liquids having different boiling-points were substituted for water. The ratio of uplift to depth of freezing for nitrobenzene, which boils at 210.85° C., is greater than for water under the same surface loads and conditions of freezing; and this is true in spite of the fact that greater force is required in pulling nitrobenzene through the clay to the growing crystals, since its viscosity at low temperatures is about 1.7 times that of water. Benzene, with a boiling-point of 79.6° C. and a viscosity of 0.5 that of water, on freezing heaves much less than does water under similar conditions. Nitrobenzene and benzene both freeze with decrease in volume at temperatures between 5° and 6° C.

It would be interesting to know the maximum tensile stress that could be developed in water as a result of freezing in an open system. By using finer material and cooling with extreme slowness, it should be possible to obtain somewhat higher tensile stress in the water, and therefore lift heavier loads, than was possible in the writer's experiments. In an ideal system it is theoretically possible to obtain a tensile stress of about 1,350 kilograms per square centimeter, but it is improbable that this stress could be approached in any attainable system.

The energy for frost heaving is supplied, of course, by the removal of heat. The greater the pressure on an ice layer the lower the temperature must be if growth is to continue. Therefore, if the films of water are not ruptured under tension, the load lifted is determined by the amount of undercooling possible in the clay immediately below an ice layer. The presence, between the base of an ice layer and the underlying soil, of a separating film connected with water below makes frost heaving a reversible action from the standpoint of thermodynamics.

When liquids that solidify with decrease in volume are substituted for water in freezing experiments with open systems, surface load, or pressure, reduces heaving, although removal of heat is the only

source of energy; and the freezing point of such liquids is raised by hydrostatic pressure acting on both liquid and solid phases.

This anomaly might be explained if we assume that the base of a crystal where growth takes place is subjected to non-uniform pressure because of adjacent soil particles, for the effect of unequal pressure would be to lower, locally, the melting-point; but this assumption seems improbable, for crystal growth would tend to equalize the pressure, and as long as the pressure is transmitted across a separating film it should be practically hydrostatic.

An alternative hypothesis is that pressure tends to reduce the thickness of the nourishing film by expelling some of the molecules and, since the expulsive forces are increased, the attractive forces must likewise be increased, by lowering the temperature, else molecules cannot enter the film. Pressure decreases molecular mobility in the film and retards crystal growth.

Growth of ice crystals under resisting pressure in open systems is analogous to the growth of crystals from solutions under similar conditions.[1] One is possible because water occupying very small voids can be undercooled; the other, because solutions in such voids can be supersaturated. Water molecules are pulled toward a growing ice crystal to replace those that become attached to it, while molecules in solutions reach their points of attachment because of osmotic pressure. If water at low temperatures is considered to be a saturated solution of trihydrol, or ice molecules in dihydrol, the analogy would be even closer; but it would be unwise to draw conclusions until more data are available. Benzene and nitrobenzene have usually been classed as non-associated liquids; but, according to Schames, molecules of $(C_6H_6)_4$ begin to appear near the freezing point in liquid benzene, which corresponds to $(C_6H_6)_2$; and Dutoit and Moijou find nitrobenzene slightly associated.[2] Tension in water should favor the formation of trihydrol molecules, and therefore of ice, in soil voids below a growing ice layer; but tension should op-

[1] Stephen Taber, "The Growth of Crystals under External Pressure," *Amer. Jour. of Sci.*, 4th Ser., Vol. XLI (1916), pp. 532–56; "Pressure Phenomena Accompanying the Growth of Crystals," *Proc. Nat. Acad. Sci.*, Vol. III (1917), pp. 297–302.

[2] Quoted in *Molecular Association* by W. E. S. Turner (London, 1915), pp. 87 and 101.

pose the formation of associated molecules in benzene and nitrobenzene, and thus help to make undercooling possible.

For one whose conceptions of frost heaving have been derived from freezing experiments with closed systems, the results obtained in this investigation seem paradoxical. (1) Heaving on clay is greater than on sand, although part of the water does not freeze in clays, whereas practically all of it, within the zone of frost penetration, freezes in sand. (2) The pressure developed during heaving in an open system is limited by the tensile stress that can be developed in the water. (3) The boiling-point of a liquid seems to be more important than the freezing-point in determining the pressure developed by freezing in open systems. (4) While water expands on freezing, the freezing of saturated clays may be accompanied by the formation of shrinkage cracks, owing to withdrawal of water to build ice layers. (5) Heaving is upward because that is the direction of heat conduction rather than because it is the direction of least resistance.

It cannot be expected that the explanation of frost heaving here given is complete and without error in all of its details. It is a first attempt and will doubtless need modification as additional data become available. A better knowledge is needed of the constitution of water and the nature of the changes occurring as the temperature is lowered and freezing takes place. Also, more must be learned about the properties of thin films of water in soils. And, it is highly desirable that accurate field observations be made of the conditions under which soil freezing is accompanied by excessive heaving in some places and no heaving in others.

THE IGNEOUS ROCKS OF SOUTHWEST ECUADOR

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ABSTRACT

The coast-belt of Ecuador, lying between 1 and 3 degrees south of the Equator, consists of Tertiary formations with which are associated igneous dikes and sills and occasional lava flows. This article deals entirely with the igneous rocks of the region, and an account is presented of the distribution, geological history, and the petrological details of the respective rock types. An attempt has been made to show that a petrographic province may occur in this region, and a correlation of the different rocks has been made which indicates that the intrusions bear a constant relation to the Tertiary formations with which they are associated.

INTRODUCTION

In the present article an attempt has been made to give some account of the hypabyssal and volcanic rocks which are found widely distributed in part of the coastal region of southwestern Ecuador, and are invariably associated with the Tertiary sediments. The whole series of intrusions is of Tertiary or post-Tertiary and pre-Quaternary age. Not infrequently the rocks are seen in close field relationship with massive and brecciated forms of chert, the latter rocks having been described elsewhere.[1]

From the map (Fig. 1) it will be observed that the region in which these igneous rocks are found extends from approximately lat. 1° south to below lat. 2° south of the Equator, and thus includes that part of the coast-belt of Ecuador from the Gulf of Guayaquil north to the port of Manta. The igneous phenomena are of sporadic regional distribution, and are found either as dikes, sills, or volcanic lavas. Farther to the south, viz., in Peru, where the coastal terrain consists of contemporaneous sedimentary formations (Tertiary), igneous rocks of the order described in the following pages are unknown.

The igneous rocks which form the subject of the present discussion have been collected from the following localities, the latter being indicated on the map (Fig. 1) by their respective numbers. With

[1] G. Sheppard, "Chert Deposits in Ecuador, South America," *Geol. Mag.*, Vol. LXV, No. 770 (1928).

one exception (viz., No. 19, Pascuales) all are hypabyssal or volcanic in origin, and occur either as dikes, sills, or as true volcanic flows.

1. Isla de la Plata
2. Punta San Lorenzo
3. Cerro de Monte Cristi
4. La Pila
5. Cerro Bravo
6. Jua, near Jipijapa
7. Punta Callo
8. Punta Salango
9. Punta Ayampe
10. East flank of Cordilleras de Colonche
11. Quiquisale
12. Cerro Alto, near Santa Elena
13. San Vicente
14. Rio Grande, near Santa Elena
15. Manantial, near Santa Elena
16. Cautivo
17. La Libertad
18. La Puntilla
19. Pascuales

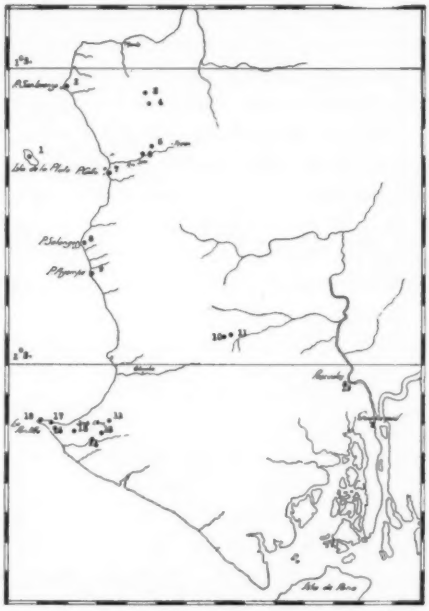

FIG. 1.—Index map of southwest Ecuador showing distribution of igneous rocks

PREVIOUS WORK

References to the igneous rocks of southwest Ecuador can be found in the following articles. (1) J. H. Sinclair and C. P. Berkey,

"Cherts and Igneous Rocks of the Santa Elena Oilfield, Ecuador," *Bull. No. 200, Am. Inst. M.M.* (1923); (2) G. Sheppard, "Relation of Volcanic Dikes to Oil-bearing Formations of S. Ecuador," *Econ. Geol.*, Vol. XXI, No. 1 (1926); (3) G. Sheppard, "Geological Observations on Isla de la Plata, Ecuador," *Amer. Jour. Sci.*, Vol. XIII, No. 78 (1927); (4) G. Sheppard, "Geology of Ancon Point, Ecuador," *Jour. of Geol.*, Vol. XXXVI (1928).

In his book on *The Geology and Paleontology of N.W. Peru* (1922), T. O. Bosworth refers to the igneous dikes which occur in Ecuador (p. 158) and certain comments of a general nature are also made by T. Wolf in *Geologia y Geografica del Ecuador* (1892), in regard to the igneous rocks of the district around Jipijapa (Province of Manabi). The latter authority, however, makes no reference to the majority of the petrological types dealt with in the present article. The more recent publications (viz., those enumerated) deal almost exclusively with the district known as the Peninsula of Santa Elena, and it is believed that many of the rock types which are described below have not been mentioned hitherto in geological literature, and it is indeed possible that they have not been previously recorded in the field.

The author is indebted to Dr. Alfred Harker, reader in Petrology to the University of Cambridge, for valuable assistance and advice in the determination of certain hypabyssal types, reference to which will be made in a later section of the article.

REGIONAL DISTRIBUTION

Commencing from the north (Fig. 1) the following prominent headlands consist essentially of igneous rock. Punta San Lorenzo (2);[1] Punta Callo (and islands) (7); Punta Salango (and islands) (8); and Punta Ayampe (9). Igneous dikes are also found in La Puntilla (18), though the greater part of the latter headland is made up of chert and altered Tertiary shales. Isla de la Plata (1), one of the largest islands off the mainland of Ecuador, is igneous in origin, consisting entirely of a basic hypabyssal rock, with the exception of certain minor Quaternary deposits.

Inland, also, both hypabyssal and volcanic forms are found in

[1] The small numbers are map references.

the vicinity of Cerro de Monte Cristi (3) and Cerro Bravo (5), the latter occurring along the valley of the Rio Seco near the town of Jipijapa. Dikes are common in this neighborhood, having been intruded through the Tertiary formations. While a certain number of these are described in a later section of this article, the list is by no means exhaustive, and undoubtedly many more exist (probably in the nature of minor dike swarms around a center of extrusion), though the recognition of these outcrops is rendered difficult by reason of the dense vegetation, and by the general inaccessibility of this virgin terrain.

Certain defined eminences in the general topography of this region are caused primarily by the presence of igneous outcrops, e.g., the conspicuous hill rising above the Quaternary tablazo, slightly inland from the coast about three miles to the north of Callo, and other elevations in a direction from the coast toward the town of Monte Cristi. Approaching farther to the south of the map-area, the eastern flank of the Cordilleras de Colonche (10) (11), the most conspicuous and extensive hill range in this part of the country, consists of basic or intermediate igneous intrusions, the latter forming large outcrops in the vicinity of Quiquisale and elsewhere.

Small igneous dikes, in association with chert masses, are found a few miles to the south of Colonche, while in the neighborhood of Cerro Alto (12), San Vicente (13), and the peninsula of Santa Elena (14) (15) (16) (17) a profusion of igneous outcrops occurs, these being found in close relationship with a disrupted and shattered suite of Tertiary formations. Masses of chert are also extensively developed in the latter region. From La Puntilla in a southeasterly direction almost as far as the settlement of San Vicente, a general line of igneous dikes intimately associated with, and flanked by, large outcrops of chert forms one of the most remarkable series of lithological phenomena in this part of the country.

In connection with the igneous masses found to the east of the Cordilleras de Colonche, it is of interest to note that at Quiquisale the basic intrusive rock is overlain by true Miocene deposits, and at the contact the Miocene limestone has a calcined or an indurated appearance which may have been induced in some way by the igneous rock beneath. From the evidence afforded by the examples in

many localities there is reason to believe that in no case have the igneous intrusions penetrated either the Miocene or the Quaternary formations. At the same time there is slight evidence to the fact that certain dikes may be post-Eocene and pre-Oligocene in age (e.g., the basal breccia of the Ancon Point Series which contains rolled pebbles, etc., of igneous rock[1]); others may possibly be of post-Oligocene and pre-Quaternary intrusion. In several instances, especially those found in the Peninsula of Santa Elena and district, and to the west of Cerro de Monte Cristi (at the settlement of Aroma), the Quaternary deposits near a dike outcrop are full of rolled pebbles and boulders of the igneous material, and not infrequently the effect of post-Quaternary denudation has exposed the dike, the outcrop of the latter having the form of large spheroids of a bluish gray doleritic rock. This spheroidal habit can be attributed to the processes of subtropical weathering, a feature which has been described as "spalling" by other authorities.[2]

DESCRIPTION OF THE INTRUSIONS

In a geological discussion of this nature there is always a certain amount of difficulty in determining the exact nomenclature of the different igneous types, as at times the field evidence may indicate that the rock is distinctly hypabyssal in character, i.e., it occurs either as a dike or as a sill. On the other hand, many of the latter types grade, in a petrological sense, to true volcanic forms, cases being not uncommon where the edge of a dike has the habit and constitution of a typical volcanic rock. "Pillow" structure and major fluxional movements in the igneous mass prior to its consolidation are not infrequently met with in intrusions of a sill type, though it must be recognized that in many examples a satisfactory differentiation between "flat" dikes and true sills is practically impossible, the two, for the purposes of petrographical argument, being synonymous rock forms.

Volcanic rocks in the nature of light-colored quartz felsites and quartz porphyries are found along the valley of the Rio Seco to the

[1] G. Sheppard, "The Geology of Ancon Point, Ecuador," *Jour. Geol.*, Vol. XXXVI (1928), p. 127.

[2] C. K. Leith, *Structural Geology* (1923), p. 57.

west of Jipijapa, near the settlement of Jua. These lava flows are all more or less of the same kind and probably originate from the crater-like mountain known as Cerro Bravo. It should be noted also that large accumulations of volcanic agglomerate (tuff), greenish ash deposits, and breccia beds are present in considerable quantity in this district. That most of the sedimentary deposits of undoubted Tertiary age which are found in this volcanic zone contain appreciable quantities of volcanic detritus (e.g., the sedimentary formations which occur along the coast from Punta San Lorenzo south to Machalilla) indicates quite conclusively that the eruptive center itself was Tertiary in age, being probably in an active state contemporaneously with the deposition of the sediments. Along the valley of the Rio Seco the Tertiary strata include beds of volcanic ash and tuffaceous breccias and, at the present time, a stream of water impregnated strongly with sulphuretted hydrogen issues from the formations, a phenomenon which probably has some connection with the ancient volcanic center near Cerro Bravo. Igneous rocks similar to these have been observed in the vicinity of Cerro de Monte Cristi, and it is reasonable to assume that this hill is of volcanic origin also, being similar in many respects to Cerro Bravo.

The hypabyssal igneous rocks found in this region include dikes and sills, all of which were undoubtedly intruded into the Tertiary sediments at a date subsequent to the volcanic episode outlined above. The most important intrusion of a hypabyssal nature can be described as the Lorenzo-Ayampe Sill, this having been recognized along the coast for a distance of at least 50 miles from Punta San Lorenzo southward to Punta Ayampe. Most of the intervening headlands, viz., Punta Callo and Punta Salango, with their respective outliers, consist of the same type of igneous rock, and it can be assumed therefore that the most westerly extension of this sill occurs as Isla de la Plata, a large island situated about 15 miles from the mainland which, as referred to in the foregoing, consists almost entirely of the same variety of igneous rock, superimposed in places by Quaternary tablazo deposits. Every outcrop of this extensive hypabyssal series presents similar petrological characters, the description appended herewith of the occurrence at Punta San Lorenzo being typical (Fig. 2).

THE SAN LORENZO INTRUSIVES

Punta San Lorenzo is one of the most westerly headlands of coastal Ecuador, its highest point being about 400 feet above sea-level. The northern flank is nearly half a mile in length, and forms a steep, almost overhanging cliff approximately 300 feet in height which extends as far as the westerly limit of the headland. Small islands or outliers of the same igneous rock are found close inshore to the mainland. The footpath which descends to the foreshore from the lighthouse marks, in a general sense, the contact between the

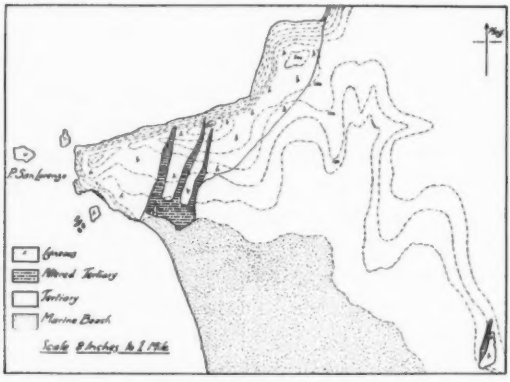

FIG. 2.—Sketch map of Punta San Lorenzo, Ecuador

igneous intrusion and the Tertiary sediments. Toward the base of the cliff the lower 10 feet form a steep ledge of dark gray igneous rock, though its actual junction with the Tertiaries is covered by the recent accumulations of beach detritus and talus material. Another inlier of igneous rock, similar in every detail to the larger mass, can be seen also a short distance to the west of San Lorenzo. The intrusion near this village is small in comparison with the principal outcrop, yet it undoubtedly forms part of the same igneous episode, being a local offshoot from the parent intrusion. This subsidiary phase which has the appearance of a sill is about 70 feet in width, the contact zone being visible on either side of the intrusion. This contact zone is directed slightly to the northwest, and the disturbed sandstones (part of which are incorporated with the igneous rock) indicate a steep dip to the northwest.

Near the junction between the igneous and the sedimentary rocks a clearly marked zone is found which can be described as a local breccia, the small, angular blocks of the intrusive rock with fragments of sandstone having been incorporated into a heterogeneous mass. It is evident also that before a state of consolidation was reached in the original igneous mass a certain amount of internal movement took place during the process of intrusion. During the cooling, the outer portion of the sill (viz., the selvage of the mass) became included in the plastic matrix, the fragments thus being

FIG. 3.—Igneous rock at Punta San Lorenzo, showing spheroidal structure

coated by a film of black glass, this having the appearance of a tachylite. Spheroidal structures are also characteristic of this intrusion, a condition in the groundmass which was formed during the process of consolidation of the flow (Fig. 3). On the other hand, however, the rock is devoid of large included cavities, as no vesicles or amygdales occur in the groundmass. The larger intrusion, which forms the headland proper, consists of a series of parallel sheets or subsidiary sills, these being separated by zones of Tertiary shale which are highly contorted and probably indurated (Fig. 2). The following phenomena have also been observed in connection with the San Lorenzo intrusives:

a) The presence of large chert masses, found in association with the sedimentaries near the contact.

b) Small groups of shattered olivine crystals are common in the groundmass, usually surrounded by zones of greenish chloritic minerals.

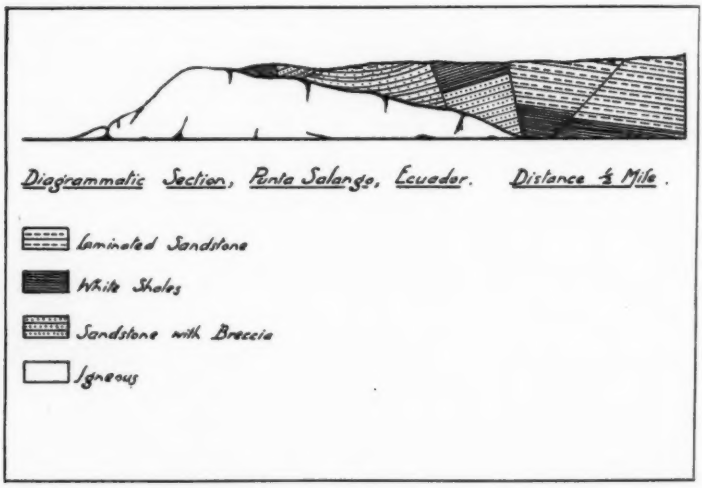

FIG. 4

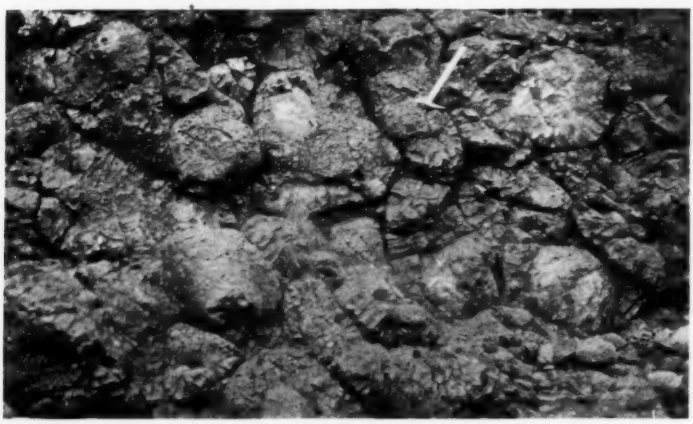

FIG. 5.—Igneous rock, at Punta Ayampe, Ecuador, showing spheroidal structure

c) Incorporated sandstone blocks are found near the contact, in addition to wedges of silicified shale.

The spheroidal structures noted in the foregoing in connection with the intrusion under consideration (Fig. 3) are probably true "pillow" forms and imply intrusion beneath a thin cover of sediment. These spheroids on a large scale have also been observed in connection with the igneous occurrences at Punta Salango, and at Isla de la Plata. Near Punta Salango the "sill" nature of the igneous mass is well exemplified, being admirably exposed in the coast section to the south of the headland (Fig. 4). The upper surface of the sill is irregular and has a hummocky appearance, yet the disturbed condi-

FIG. 5*a*.—General aspect of sill, Punta Salango, Ecuador

tion of the overlying sandstones and shales indicates conclusively the nature and direction of the original intrusion (Figs. 5 and 6). It is of interest to note that Isla de Salango, situated about half a mile away from the headland of the same name, consists of precisely similar igneous rock and forms undoubtedly a westerly extension of the same intrusion. Large nodules or irregular blocks of chert are again a characteristic feature of this area and occur in considerable profusion near the contact between the igneous and the sedimentaries (Fig. 7). The headland known as Punta Callo (Fig. 8) presents geological features which are similar in many respects to the occurrences recorded above at Punta Salango. The tip of Punta Callo (and the islands close inshore) consists of a dark gray igneous rock, which contrasts sharply with the lighter colored Tertiary shales which it intrudes. Near the contact the shales are heavily veined by silica

and, in addition, large masses of brecciated chert occur, a phenomenon which has been noted elsewhere in connection with this group of igneous intrusions (Fig. 7).

Punta Ayampe, known also as the Cinco Cerros, consists mainly of hypabyssal igneous rock, and occurs in the form of a sill which has been intruded into the Tertiary shales and sandstones. From the field relations of the different formations, and a microscopic correlation of the various igneous types, it can be considered that

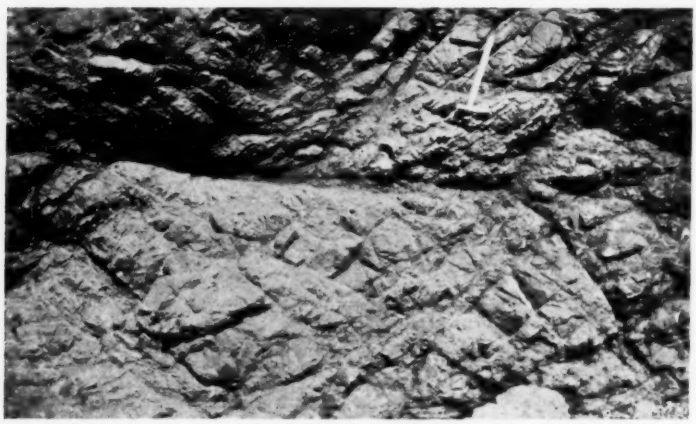

FIG. 6.—Face of igneous outcrop, Punta Salango, Ecuador

the occurrences at Punta Ayampe form part of the Lorenzo-Ayampe Sill, having similar petrographic characters to the rocks found at Punta Salango and Punta San Lorenzo.

In the peninsula of Santa Elena proper a defined line of igneous dikes occurs from the tip of the headland (La Puntilla), extending in a southeasterly direction almost as far as San Vicente. The type rock is dark green or gray in color, being probably a dolerite, and varies from micro- to medium-crystalline in character. Large masses of white and gray chert are usually associated with these igneous dikes. A series of hypabyssal intrusions is also found to the east of the main range of the Cordilleras de Colonche, extending eastward as far as the settlement of Quiquisale, at which point it disappears beneath the Miocene formations. The conspicuous hill along the

coast about 3 miles to the north of Callo consists largely of hypabyssal rocks and in all probability forms the western extension of a

FIG. 7.—Chert masses at contact of igneous and Tertiary, Punta Salango, Ecuador

FIG. 8.—Punta Callo, Ecuador

number of similar outcrops which are found inland toward Monte Cristi.

Igneous dikes of the same megascopic appearance as the occurrences noted in the foregoing have been observed to the west of

Cerro de Monte Cristi, viz., near Aroma and Pacoche. They are exposed also near La Pila and are found along the valley of the Rio Seco near Jipijapa. At La Puntilla the igneous rock occurs in the form of small dikes intruded through the Tertiary shales, the dikes themselves rarely exceeding a few feet in thickness. In the same locality a medium-grained type is also found in the habit of small pear-shaped masses (ranging from a few inches to 2 or 3 feet in length), being intimately associated with the light-colored cherts which form the major portion of the headland. The presence of these small masses, or "gobbets," of igneous rock in contact with the chert is unusual, though a similar geological condition has been recorded previously in connection with certain cherts found in England.[1] At La Puntilla, however, it appears that the igneous masses are found in association with certain major fault planes in the cherts and altered Tertiary shales, and thus may represent the upper part of a more deep-seated igneous mass, having been forced upward whilst in a semimolten condition through a plane of weakness in the country rock, and hence being distributed in the curious forms described.

The igneous outcrop at Cerro Alto, to the north of San Vicente, has been mapped in order to show its field relationship with the Tertiary sandstones and the cherts. From the diagram (Fig. 9) it will be seen that the outcrop of the igneous rock is relatively small, yet it appears to have been intruded through the Tertiary sediments, with a formation of chert and a silicification of the normal type of sandstone. In this instance the sedimentary rocks are highly inclined (approximately at the same angle as the dike); they are also faulted and dislocated to a considerable extent.

PETROLOGICAL DETAILS

With the exception of the plutonic form found at Pascuales (19) and the light-colored quartz porphyries and quartz felsites of the Monte Cristi and Cerro Bravo districts, the examples described in this article are rocks, dark gray in color, which vary in texture from fine or microcrystalline, to medium-grained hypabyssal types of igneous rock. From the petrographic descriptions appended here-

[1] Kendall and Wroot, *Geology of Yorkshire* (1924), p. 221.

with it will be seen that the whole group can be classified as dolerites, these being further subdivided into olivine dolerites, quartz dolerites, analcite dolerites, and tholeiites. The marginal portions of the respective intrusions are not infrequently glassy in texture and are occasionally vesicular. In connection with the two specimens collected from Isla de la Plata, Dr. Alfred Harker, of Cambridge University, makes the following observations:

They are more or less of the tholeiite type, though not quite what is understood by that name. They are microporphyritic, with plagioclase and augite

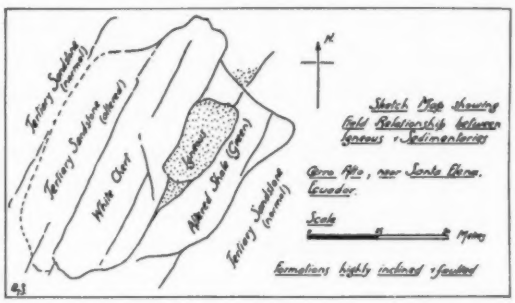

FIG. 9

in a fine-textured groundmass. The groundmass of one is mainly of feathery microlites of feldspar, with some interstitial glass and magnetite. The other example has also a fair amount of augite in the ground in little irregular patches.[1]

In a general way the group is characterized by the presence of porphyritic plagioclase, this being of the labradorite-anorthite or bytownite group, which exhibits twin lamellation on the albite law. Glomeroporphyritic structure with zoning is also present in certain examples. The principal ferro-magnesian mineral is a purplish-brown augite (titanaugite) usually showing sensible pleochroism. This mineral occurs in large plates ophitically enclosing the feldspars; it is also granular in habit and not infrequently forms idiomorphic crystals showing the characteristic cleavage. The alteration of this augite gives rise to skeletal ilmenite, with a separation of gray leucoxene, and occasionally a "corona" structure is formed by fibrous green outgrowths of bastite or chlorite, derived from the original

[1] Alfred Harker, personal communication.

augite crystal. Hornblende occurs occasionally, and when present is found in well-defined phenocrysts. That this group of hypabyssal rocks is more of an intermediate than a basic character is suggested by the presence of quartz, which occurs in several types as an accessory constituent. In certain examples this mineral occurs in sufficient quantity as to determine the variety of the rock, e.g., quartz dolerite. As a general rule the quartz occurs as a primary mineral, being intergrown with the feldspar.

In this connection the presence of quartz in the hypabyssal rocks of the region under consideration, in the volcanic types of Monte Cristi and Cerro Bravo, and in the plutonic "syenite" of Pascuales is strongly suggestive of a petrographic province of considerable regional extent, which may be genetically related to the older igneous rocks which form the core of the present Andes.

Analcite and olivine are present in certain types found in this district, occurring usually in sufficient quantity to qualify the rock name. Mica is conspicuously absent, and even if it had occurred originally as a constituent it has since been resorbed into secondary minerals and hence obliterated as a recognizable form in the groundmass. In addition to the ilmenite, which occurs in both euhedral and skeletal forms, true magnetite is a common accessory mineral, as well as small specks of iron pyrites.

Although the general texture of the igneous rocks under present discussion varies from fine (micro- or crypto-crystalline) to medium (megacrystalline) grain it must be remembered that in many cases this structural variation in the lithology of the rock may take place in the same intrusion within very short distances. The marginal portion of a dike or sill, i.e., at its zone of contact with the intruded sedimentaries, is not infrequently glassy or cryptocrystalline, this feature being occasioned by the more rapid cooling of the igneous mass. A relatively deeper-seated portion of the same intrusion, however, which has cooled more slowly has, as a consequence, a coarser structure in the groundmass. The marginal parts of the intrusion have frequently suffered devitrification, a phenomenon which is quite common in several examples.

Local variations in structure are found in most of the igneous types considered in the present article, and in this connection the

following examples may be quoted: The two specimens collected from Manatial Hill, in the Santa Elena district, were obtained from the same intrusion at points not more than 30 feet apart. Both are typical dolerites (olivine and analcite, respectively) and undoubtedly represent local variations of the same hypabyssal rock. Other types which bear a certain petrological relationship can be grouped as follows: La Libertad and La Puntilla (quartz dolerites); Punta Salango (dolerites); specimens from east flank of the Cordilleras de Colonche (dolerites and trachydolerites); and specimens from Punta Ayampe, Punta Callo, and from the intrusions of the Rio Seco.

The quartz-bearing igneous rocks collected in the vicinity of Cerro de Monte Cristi and Cerro Bravo (Province of Manabi) form a distinct type from the other intrusive rocks referred to in the foregoing, and they probably represent lava flows of an acid nature, thus indicating a regional differentiation in the petrogenesis. In this connection the "syenite" of Pascuales is not without interest.

SUMMARY OF CONCLUSIONS

The igneous rocks which occur in the region under present discussion can be considered under the following groups: (1) plutonic, viz., the syenite of Pascuales; (2) hypabyssal, the dikes and sills which intrude the Tertiary sediments; (3) volcanic, the lava forms which are found in the vicinity of Cerro de Monte Cristi and Cerro Bravo.

The igneous types include, respectively, syenites, dolerites, and quartz-porphyries and felsites, an intermediate group of rocks which probably expresses a complete petrographic province occurring in this region. In contrast with Peru, where intrusive igneous rocks of this order are unknown in association with the same suite of Tertiary formations, the presence of these igneous types in southwest Ecuador is not without interest, and it is believed that the dikes and sills have been intruded as a consequence to regional "foundering" of the Tertiary belt west of the main Andes.[1] The structural deformation of the coast-belt, with its repetition of faulted blocks of a more or less normal order, is suggestive more of "foundering" than of

[1] G. H. S. Bushnell.

direct tectonic disturbance. It is indeed difficult to accept the theory that the irregularly faulted condition of the Tertiary formations of this region has been caused by the tectonic influence of the major Andean uplift; neither can the idea of a geologic "hinge" upon the margin of an extensive geo-fault be applied satisfactorily in accounting for the peculiar structural conditions which obtain in connection with the sedimentary formations of this part of the country.

TRIASSIC-JURASSIC RED BEDS OF THE ROCKY MOUNTAIN REGION

ANOTHER DISCUSSION[1]

JOHN G. BARTRAM
Denver, Colorado

ABSTRACT

This article is a discussion of four detailed cross-sections that show correlations of the Triassic-Jurassic red beds in Wyoming. Individual beds have been recognized and traced over considerable areas, so that correlations can be satisfactorily made with the type localities of the Sundance formation in the Black Hills and of the Chugwater formation north of Cheyenne. It is concluded that the name Chugwater should only be used in the "restricted" manner suggested by Reeside; that the Jelm should be enlarged to include all Upper Triassic beds; and that the Nugget sand and overlying red beds belong in the Sundance formation.

The correlation of the Triassic-Jurassic red beds of the Rocky Mountain region, particularly in Wyoming, has been the subject of an interesting discussion between Branson[2] and Reeside.[3] Although each has studied the subject for many years, their interpretations are quite different. The principal differences are that Branson places all the "red beds" in Wyoming in one unit, the Chugwater, and does not believe that the "red beds" can be subdivided, whereas Reeside argues that the "red beds" can be subdivided into several units of different age, that the upper units are Jurassic in age, and that the name "Chugwater" should be used only in a restricted sense.

The present writer enters the discussion in support of most of Reeside's correlations, but this article is restricted largely to Wyoming and only parts of the adjoining states, since the writer has not studied the entire Rocky Mountain area. He has worked mostly in Wyoming for the last six years in the employ of a major oil company. In the work a large number of detailed surface sections have been measured, and in the laboratory well cuttings and surface samples have been examined and correlated, and the "red beds"

[1] Published with the permission of the Midwest Refining Company.

[2] *Jour. Geol.*, Vol. XXXV (1927), pp. 607–30; *ibid.*, Vol. XXXVII (1929), pp. 64–76.

[3] *Ibid.*, Vol. XXXVII (1929), pp. 47–64.

have been subdivided and correlated successfully for some time. Since Branson and Reeside have not published detailed sections and correlations, the cross-sections and correlations in this article should assist in the solution of the problem. In four cross-sections drawn at various angles across Wyoming, fourteen measured stratigraphic sections and the sample logs of two deep wells are shown.

The writer believes that Branson has not recognized two important points: first, that the Sundance formation at its type locality in the Black Hills[1] admittedly contains "red beds," a middle member of red sandstone and red shale and a basal reddish sandstone; second, that detailed stratigraphic work will show that the Chugwater formation at its type locality on the east side of the Front Range[2] represents only the lower 800 feet of what he calls Chugwater in the Wind River Mountains, and that the upper 600 feet of the Wind River section is very nearly absent at the eastern locality. The upper beds do not grade eastward into "red beds" that cannot be distinguished from the lower "red beds" as Branson argues. There are excellent horizon-markers in the "red beds," the Alcova limestone,[3] a gypsum bed and an oölitic limestone above the Nugget sandstone, and the Nugget sandstone itself, whose grains have a peculiar rounded and etched appearance under the microscope. These and other markers have been used successfully, and can be traced for long distances.

DESCRIPTION OF CROSS-SECTIONS

The first cross-section (*A-A*) extends from the northwest corner of Colorado across Wyoming in a northeasterly direction to the south end of the Black Hills in South Dakota. It includes the Vermillion Creek section by Sears[4] on the east end of the Uintah

[1] N. H. Darton, "Sundance Folio," *U. S. Geol. Survey Geol. Atlas, Folio 127.*

[2] N. H. Darton, "Comparison of the Stratigraphy of the Black Hills—Big Horn Mountains and Rocky Mountain Front Range," *Bulletin Geol. Soc. Amer.*, Vol. XV (1904).

N. H. Darton, Eliot Blackwelder, and C. E. Siebenthal, "Laramie-Sherman Folio," *U. S. Geol. Atlas, Folio 173* (1910).

[3] W. T. Lee, "Correlation of Geologic Formations between East-Central Colorado, Central Wyoming and Southern Montana," *U.S. Geol. Survey Paper 149* (1927), p. 14.

[4] J. D. Sears, "Geology and Oil and Gas Prospects of Part of Moffat County, Colorado, and Southern Sweetwater County, Wyoming," *U.S. Geol. Survey Bull. 751* (1924), pp. 277, 280, 284.

Mountains; a section at Bell Springs, north of Rawlins; one at Alcova, southwest of Casper; one near Douglas; and one for the south end of the Black Hills compiled from Darton's work.[1] The top of the big Pennsylvanian sandstone, which in various places is named the Weber, Tensleep, and Minnelusa, is the base of all the sections. This cross-section connects the Vermillion Creek section, which can be correlated very well with other sections of eastern Utah, with the Black Hills where the Jurassic beds have been described in detail.

The Permian Park City formation is present at Vermillion but is not so thick as it is farther west, north, and northwest. Above it Sears shows 750 feet of sandy shales and some thin sandstones which he correlates with the Thaynes and Woodside of northeastern Utah. These beds are locally gray, but elsewhere in that vicinity they are quite red in color. Directly above them is a coarse, conglomeratic, gray sandstone which Sears included with the red sandy shales and sandstones above, and correlated with the Ankareh. The writer believes that the conglomeratic sandstone is the Shinarump of Utah, the beds below it the Moenkopi, and the beds above up to the base of the Nugget sandstone the Chinle.

The thick Nugget sandstone is separated into two parts in the area by a streak of bright red shale, a condition that is reported by other geologists to prevail fairly generally in eastern Utah. It is probable that the upper member is the Navajo sandstone, the red break the Todilto, and the lower sandstone, the Wingate. Above the Nugget sandstone are the Jurassic green shales and fossiliferous limestones of the Twin Creek formation and the variegated shales and sandstones of the Beckwith.

Tracing the beds farther east to the other sections, the gray limestones of the Park City or Embar begin to have a red tint at Bell Springs, and there appears also some of the purple color that is so characteristic farther east. At Alcova much of the limestone is gone and the Embar is largely red shale and gypsum, with only a little purple limestone. At Douglas the purple limestone is very prominent, and there can be little doubt about its correlation with the Minnekahta of the Black Hills.[2] At Alcova, Douglas, and the Black Hills

[1] N. H. Darton, "Edgemont Folio," *U.S. Geol. Survey Geol. Atlas, Folio 108.*

[2] N. H. Darton and Sidney Paige, "Central Black Hills Folio," *U.S. Geol. Survey Atlas, Folio 219* (1925).

above the purple limestone are several gypsum beds alternating with red shales. At Alcova they have generally been considered to belong to the Embar, and therefore are probably of Permian age, whereas in the Black Hills they are placed in the Spearfish of Triassic age. The writer believes the gypsum beds are approximately the same at the two localities and that in central Wyoming there is not the sharp break that is assumed by many geologists between the Permian, Park City, or Embar, and the Triassic, Chugwater, or Spearfish.

The Thaynes and Woodside at Vermillion Creek extend east to form the Chugwater in the "restricted" usage of Reeside, and at Bell Springs there has appeared, at or close to the top of the unit, the prominent Alcova limestone which is probably an eastern extension of a lime horizon in the Thaynes. This is an excellent key horizon over much of central Wyoming but disappears to the east and north. The Chugwater formation continues eastward with the same characteristics to Douglas and the Black Hills, except that the Alcova limestone is absent and the "red beds" are thinner in the Black Hills.

Directly, or a short distance, above the Alcova limestone there is an abrupt change in the character of the rocks. Those below the Alcova are red sandy shales grading upward into shaly sandstones of a uniform bright red color, whereas above it there are gray sandstones, red sandstones, and reddish sandy shales that give the beds a distinct banded appearance. At some places these beds do not have the gray sandstones and are more red and purple, soft sandstones and sandy shales. There should be no difficulty in distinguishing them in the field from the underlying "red beds," or from the more massive Nugget sandstone above. It is this unit between the horizon of the Alcova limestone and the base of the Nugget sandstone that contains the Jelm[1] and Popo Agie[2] beds whose vertebrate fossils have caused much discussion. The writer believes that this unit is equivalent to the Chinle and Shinarump of Utah, and that

[1] S. H. Knight, "Age and Origin of the Red Beds of Southeastern Wyoming," *Jour. Geol.*, Vol. XXVIII (1917), p. 168.

[2] S. W. Williston, "Notice of Some New Reptiles from the Upper Trias of Wyoming," *Jour. Geol.*, Vol. XII (1904), p. 688; E. B. Branson, "Origin of the Red Beds of Western Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XXVI, pp. 220–21.

if the Popo Agie and Jelm are not exactly equivalent to each other and to the Shinarump, they are very nearly so. He suggests, following the lead of Reeside,[1] that the name Jelm be chosen for this unit, that the other be dropped, and that for practical field purposes its usage be broadened to include all the beds from the top of the "restricted" Chugwater (at or close to the top of the Alcova limestone) up to the base of the Nugget sandstone. Jelm in this new usage would include all the beds believed to be Upper Triassic in age. These beds thin out to the northeast and are entirely absent in the Douglas and Black Hills sections.

Next higher in the section is the thick Nugget sandstone which at Vermillion Creek has three members that might be correlated with the Navajo, Todilto, and Wingate formations of Utah. The Nugget thins to the east, but is still a massive bed at Bell Springs. It is not known whether all its members thin evenly or whether some parts have disappeared. At Alcova, Douglas, and the Black Hills it is progressively thinner, but it certainly is still present, for the peculiar microscopic characteristics of the Nugget sandstone can be correlated. It is quite certainly the basal red sandstone of Darton's Sundance in the Black Hills and is the Sundance sand of the petroleum geologists, producing oil in the Iles field of Colorado and the Lost Soldier and Salt Creek fields in Wyoming.

If one turns next to the eastern end of cross-section A-A, Darton's southern Black Hills section shows that the Sundance can be divided into four distinct units: a basal red sandstone, which this article correlates with the Nugget; a gray, slightly sandy shale that contains some Jurassic fossils; a thickness of nearly 100 feet of bright red sandstones and red sandy shales; and an upper member of gray-green shales and fossiliferous limestones. For convenience in the field, some geologists are naming these four units, the Sundance sand, the Lower Sundance shale, the Middle Sundance "red," and the Upper Sundance shale. These names will be used in this article. Following these units back toward the west, they can be distinguished readily at Douglas and Alcova, and a gypsum bed is found at the base of the Middle Sundance "red." Still farther west, the

[1] John B. Reeside, Jr., "Triassic-Jurassic Red Beds of the Rocky Mountain Region: A Discussion," *Jour. Geol.*, Vol. XXXVII (1929), p. 58.

upper Sundance shale is present at Bell Springs and at Vermillion Creek (where it is called Twin Creek), but the Middle Sundance "red" appears at only Bell Springs, and the Lower Sundance shale is absent at both places.

CROSS-SECTION B-B

This next cross-section extends from the Dallas Anticline[1] on the east side of the Wind River Mountains southeastward to the same Bell Springs section near Rawlins, and then eastward to sections at Elk Mountain, Como Ridge, near Medicine Bow, and to one measured by Lee[2] on Mill Creek near Horse Creek north of Cheyenne. It connects the Wind River section that Branson regards as typical of the Chugwater with the locality of Darton's type Chugwater east of the Front Range, and shows the gradations and differences between the two.

At the base of the sections, the change of the gray limestone of the Park City eastward into red shales and purplish limestones can be traced without much difficulty. It is believed that the drab-colored beds of the Dinwoody formation grade into the lower part of the Chugwater. On the east end of the section, the pronounced thickening of the Forelle and Satanka, or Casper formation, is related to the Carboniferous problem of the Laramie Basin and northern Colorado and need not be discussed here, except to state that the Permian and Pennsylvanian beds change rapidly to the south as they approach an old land mass.

At Horse Creek Darton's original Chugwater would include everything from the top of the massive Pennsylvanian sandstone to the bottom of the basal sandstone of the Sundance. The newer "restricted" Chugwater includes the strata from the top of the Forelle limestone to the base of the same Sundance sandstone, a thickness of about 600 feet. This unit of Chugwater "red beds," evenly bedded, bright red sandy shale and shaly sandstone can be traced westward, and is less than 800 feet thick at Dallas. The Alcova limestone is at or close to the top of this unit at Dallas and Bell Springs, but does not extend farther east.

[1] E. G. Woodruff, "The Lander Oil Field, Wyoming," *U.S. Geol. Survey Bull. 452* (1911).

[2] W. T. Lee, *U.S. Geol. Survey, Professional Paper 149* (1927), pp. 40–41.

At Dallas, the typical Popo Agie beds are just above the Alcova limestone. The name has been used only for a relatively thin, partly conglomeratic sandstone with vertebrate remains, but the beds from the Alcova limestone up to the base of the Nugget sandstone can well be grouped together, since the softer red and purple sandstones, partly shaly are very different from the "red beds" below the Alcova limestone, and from the more massive, white, pink to purple Nugget sandstone above. It has, therefore, already been suggested in this article that the Popo Agie be extended upward to the base of the Nugget sandstone and called the "Jelm." This unit would include about 275 feet of beds at Dallas and is regarded as equivalent to the Chinle and Shinarump of Utah. At Bell Springs a greater thickness is shown for this Popo Agie or Jelm unit, but there is a possibility that some of its upper part may belong in the Nugget sandstone. At Elk Mountain and Como Ridge the unit is thinner, but includes typical Jelm deposits. At Horse Creek, the Jelm has disappeared. The Nugget sandstone can be traced through the entire cross-section in clear-cut fashion.

At Dallas, above the Nugget sandstone, the three other members of the Sundance formation are well represented. The typical gray-green shale and fossiliferous limestones of the Upper Sundance shale can be traced through the cross-section. The Middle Sundance "red" can also be followed to the east in good shape. The Lower Sundance shale is present but with it are some limestones, red shale, and gypsum that do not occur farther east. They cover a large area to the north and northeast, and if another cross-section were drawn northeast from Dallas to the Black Hills, the members of the Lower Sundance shale unit could be well correlated on it. The gypsum bed and an oölitic limestone of this unit have made excellent horizon-markers that have been carried long distances. Jurassic fossils have been described from this unit by Brainerd and Keyte.[1]

Summarizing the correlations on cross-section *B-B*—on Horse Creek the "restricted" Chugwater is 600 feet thick, the Jelm is absent, the Nugget or Sundance sand is 30 feet thick, and the remain-

[1] A. E. Brainerd and I. A. Keyte, "Some Problems of the Chugwater-Sundance Contact in the Bighorn District of Wyoming," *Amer. Assoc. of Pet. Geol.*, Vol. XI (1927), p. 747.

der of the Sundance formation above the sandstone is about 50 feet thick. At Dallas the "restricted" Chugwater is 750 feet thick, and 850 feet if it includes the Dinwoody; the Jelm in the broader usage just suggested, is 275 feet thick, and the total of the lower, middle, and upper Sundance units is about 300 feet. The interval of 650 feet for the Nugget and Jelm at Dallas is represented by only 30 feet of Nugget sandstone at Horse Creek.

CROSS-SECTION C-C

The third cross-section connects with central Wyoming a section in western Wyoming, which can be correlated with the published Idaho sections.[1] The western Wyoming section was measured on La Barge Creek, 40 miles north of Kemmerer. It is correlated first with the section at Dallas, then with one at Arminto on the south end of the Big Horn Mountains, and with the sample log of a deep well in the Salt Creek oil field. On the west, the Park City is very thick and has been mapped for phosphate over large areas. It thins to the section at Dallas and farther east rapidly changes to red shale and gypsum, with a minor amount of purple limestone. The Thaynes and Woodside have already been correlated on cross-section A-A with the "restricted" Chugwater. The Alcova limestone is correlated provisionally with the upper limy member of the Thaynes, but it may be a lower limestone in the Thaynes. The Ankareh of LaBarge Creek is correlated with the Jelm (in the broader usage just suggested) and is traced through to the Salt Creek well, but thins to the east. The Nugget sandstone is also present in all the sections and steadily thins as it extends east.

The Twin Creek of western Wyoming is correlated with the Sundance formation by everyone, but it is not known yet how the various units of the Sundance carry through into the very different section of the Twin Creek. That formation on La Barge Creek is composed of 1,000 feet of gray limestone and limy shale with two fairly prominent pink shale horizons, one at the base and the other slightly below the middle. Additional work can well be done between the western Wyoming area and the Wind River Mountains, perhaps in the Gros-ventre Mountains, to determine the exact rela-

[1] G. R. Mansfield, "Geography, Geology and Mineral Resources of Part of Southeastern Idaho," *U.S. Geol. Survey, Professional Paper 152* (1927).

tion of the Twin Creek to the various units of the Sundance. It is suggested here that the Twin Creek of western Wyoming may be largely equivalent to the lower and middle parts of the Sundance and with perhaps some of the upper part, and that the lower part of the Beckwith formation may be equivalent to at least some of the upper part of the Sundance. In that event, Sears' Twin Creek at Vermillion Creek may be equivalent to only part of the Twin Creek of western Wyoming.

The measured sections at Dallas and Arminto and the well at Salt Creek all show the oölitic limestone in the Lower Sundance shale, and all the three units of the Sundance can be traced eastward with certainty.

CROSS-SECTION D-D

The last cross-section is drawn along the northern edge of Wyoming and extends into southern Montana. It is nearly outside of the area discussed by Branson and Reeside, but is included here to give some idea of the manner in which the formations are changing northward. The cross-section extends from the Shoshone Canyon at Cody to Little Sheep Mountain south of Lovell, to Pryor Mountain east of Frannie, and then to a well on the Woody Creek anticline on the east side of the Big Horn Mountains, in Montana.

The Park City or Embar limestones change to red shale and gypsum and thin as they extend eastward, exactly as they do farther south. The "restricted" Chugwater at Shoshone Canyon is somewhat thicker than it is in the sections to the south, and may include some beds equivalent in age to the Jelm or Nugget, but that does not appear to be the case. The Chugwater thins to a normal thickness in the other sections, but the Alcova limestone is absent in all of them. Apparently the Jelm and the Nugget are entirely absent in this north area. Directly above the "restricted" Chugwater at Shoshone Canyon is the thick gypsum bed that overlies the Nugget sandstone at Dallas, and above the gypsum is the persistent oölitic limestone. The gypsum and the limestone with some gray shale above them are placed in the Lower Sundance unit. The middle "red" unit is present but is changing to a thicker shale body, has lost its sandy character, and is pink rather than bright red. Above it the Upper Sundance unit is also thicker but still has its same green

color and fossiliferous limestones near the top. It is 400 feet thick and is quite sandy in its upper part. The units of the Sundance formation have not been conclusively correlated yet with the Ellis of Montana, but it is suggested that the Ellis may be largely equivalent to the Middle Sundance unit and perhaps to part of the Upper unit.

In Montana there is a large unconformity between the Jurassic Ellis formation and the underlying beds, and it increases in importance to the north until the Ellis rests on Madison limestone of Mississippian age. The writer believes that beds equivalent to the Pennsylvanian Tensleep, Permian Park City, and Lower Triassic Chugwater formations were deposited over most of Montana, and then were eroded to their present condition in either Upper Triassic, Jelm time, or in Middle and Lower Jurassic, Nugget time, or in both periods. In places in northern Montana and southern Alberta a sandstone is found at the unconformity, and the writer believes that it should be correlated with the Nugget sandstone. After this period of erosion, the Upper Jurassic sea invaded the region, depositing first the members of the Lower Sundance unit in only part of the area, and finally overspreading the entire area to deposit the other Sundance beds, the Twin Creek and the Ellis formation.

CONCLUSIONS

The "red beds" of Wyoming have been successfully divided into units that are traced and correlated from one area to another, and the writer favors the division and nomenclature suggested by Reeside. For field purposes it seems best to separate the Pennsylvanian, Permian, Triassic, and Jurassic strata in Wyoming into the following formations:

1. The thick and prominent Pennsylvanian sandstone, variously called the Weber, Tensleep, and Minnelusa sandstone.

2. The Permian limestones series that grades eastward into red shales, gypsums, and thin purple limestones, named in different places the Park City, Embar, Minnekahta limestone and Opeche shale, and the Forelle limestone and Satanka shale.

3. The Lower Triassic "red beds," whose top is at or close to the Alcova limestone, and should be called the Chugwater in the "restricted" usage.

4. The Middle and Upper Triassic unit of red, gray, and purple sandstones, partly conglomeratic, and carrying some vertebrate remains. Beds in this unit have been named Jelm and Popo Agie. It is proposed that the unit be broadened upward to the base of the Nugget sandstone, and, as Reeside has suggested, that it be called the Jelm formation.

5. The Jurassic beds have been named the Sundance formation, and that name should stand, with the recognition that the Nugget sandstone and the gypsum, red shale, and limestone directly above the Nugget belong in the Sundance. It is possible to divide the Sundance into four units that are now called by some geologists the Nugget or basal Sundance sandstone, the Lower Sundance gray shale, the Middle Sundance "red," and the Upper Sundance gray or green shale.

A problem yet to be solved is the correlation of the divisions of the Sundance formation with the Ellis formation of Montana and the Twin Creek formation of western Wyoming and Idaho.

A PETROGRAPHIC STUDY OF THE MADISON AND JORDAN SANDSTONES OF SOUTHERN WISCONSIN

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ABSTRACT

The Madison-Jordan sandstone unit is a part of the late Cambrian formations of the Upper Mississippi Valley. The sandstones are described in some detail and the results of the studies of composing minerals are given. The minerals are divided into the two groups of "light" and "heavy," using the "heavy" liquid tetrabromoethane to make the separation. The "light" minerals compose the major portion of the sandstones and are mostly quartz with a little feldspar. The "heavy" minerals are more than 75 per cent garnet, usually more than 85 per cent, and small quantities of zircon and tourmaline, the latter in the minority. The "heavy" constituents of the sandstone suggest that sedimentary terranes were the immediate sources from which the materials of the sandstones were derived.

INTRODUCTION

The Madison sandstone and the Jordan sandstone of the late Cambrian have been considered by some as two formations, the Madison in its best development occurring in southeastern Wisconsin and the Jordan in western Wisconsin. The Madison contains marine fossils and is of marine origin; the Jordan has yielded no fossils and its origin has not been determined. Each immediately underlies the Oneota dolomite of the early Ordovician. Some students have considered the two sandstones as equivalent; others, particularly Ulrich,[1] regard the Madison as succeeding the Jordan.

A study of the minerals in the two sandstones was undertaken with the hope that such a study might assist in solving the relationships of the sandstones to each other. To this end careful collections were made from Madison and Jordan sections in both eastern and western Wisconsin, samples being taken from every foot of each section studied. The samples cover a territory of 150 miles from east to west and 40 miles from north to south. It was found that the

[1] E. O. Ulrich, "Major Causes of Land and Sea Oscillations," *Washington Acad. Sci. Jour.*, Vol. X (1920); pp. 57–68; "Notes on New Names in Table of Formations and on Physical Evidence of Breaks between Paleozoic Systems," *Trans. Wisconsin Acad. Sci., etc.* Vol., XXI (1924), pp. 71–107.

minerals of the Madison and Jordan sandstones are strikingly similar in varieties, physical characteristics, and quantities; that the constituents of the two sandstones were probably derived from the same terrane—unless the Madison derived its material from the Jordan—and that the supplying terrane probably was of sedimentary origin. The mineral studies suggest that the two sandstones are the same, each deposited in an environment somewhat different from the other. To this view the suggestion of Ulrich that the Mendota dolomite lies between the two sandstones is adverse, but as this dolomite in no place has been seen in this position, the latter suggestion cannot be given weight equal to that based on studies of constituent minerals.

The writer wishes to acknowledge the assistance of Dr. W. H. Twenhofel in directing the research, and the helpful suggestions and criticism of Dr. J. E. Hawley. The work was done in the Sedimentation Laboratory of the University of Wisconsin.

CHARACTERISTICS OF THE MADISON AND JORDAN SANDSTONES

The Paleozoic section in eastern Wisconsin, near Madison in particular, shows almost 300 feet of Cambrian sandstones capped by early Ordovician dolomite. Thwaites[1] describes the Madison section as follows:

	Feet
Oneota dolomite	40
Madison sandstone	39
Mendota dolomite	20
Mazomanie sandstone	110
Dresbach sandstone	100

The section in the Tomah and Sparta quadrangles, 100 miles northwest of Madison, described by Twenhofel and Thwaites[2] is the following:

	Feet
St. Peter	70
Oneota dolomite	0–170
Madison sandstone	0– 16
Jordan sandstone	26– 40
St. Lawrence sandstone	78–110
Franconia sandstone	120– 73
Dresbach sandstone	590–615

[1] F. T. Thwaites, "Paleozoic Rocks Found in Deep Wells in Wisconsin and Northern Illinois," *Jour. Geol.*, Vol. XXXI (1923), p. 530.

[2] W. H. Twenhofel and F. T. Thwaites, "The Paleozoic Section of the Tomah and Sparta Quadrangles, Wisconsin," *ibid.*, Vol. XXVII, (1919), pp. 228–29.

The two sections show that the Madison lies below the Oneota dolomite in eastern Wisconsin, and the Jordan sandstone, with questionable Madison sandstone above, holds the same position in western Wisconsin.

TABLE I

Slide No.	Colorless Garnet	Pink Garnet	Total Garnet	Zircon	Tourmaline	Rutile	Epidote	Staurolite	Cyanite	Zoisite
1	81	15	96	3	1	.....	.....	.....	.....	.....
2	82	8	90	9	1	.....	.....	.....	.....	.....
3	83	10	93	7	×	.....	.....	.....	.....	.....
4	85	5	90	10	×	×	.....	×	×	×
5	79	14	93	7	×	×	.....	.....	.....	.....
6	91	6	97	3	×	×	.....	.....	.....	.....
7	87	8	95	5	×	.....	.....	.....	.....	.....
8	85	6	91	8	1	.....	.....	.....	.....	.....
9	80	11	91	7	2	.....	.....	.....	.....	.....
10	88	4	92	8	×	×	.....	.....	.....	.....
11	84	7	91	8	1	×	.....	.....	.....	.....
12	77	18	95	5	.....	.....	.....	.....	.....	.....
13	90	6	96	4	×	.....	.....	.....	.....	.....
14	88	8	96	4	×	.....	×	.....	.....	.....
15	85	8	93	7	×	.....	×	.....	.....	.....
16	88	4	92	8	.....	.....	.....	.....	.....	.....
17	87	8	95	5	×	.....	.....	.....	.....	.....
18	84	12	96	4	×	.....	.....	.....	.....	.....
19	84	10	94	5	1	.....	.....	.....	.....	.....
20	88	8	96	4	.....	.....	.....	.....	.....	.....
21	89	9	97	2	1	.....	.....	.....	.....	.....
22	86	10	96	4	×	.....	.....	.....	.....	.....
23	83	12	95	3	2	.....	.....	.....	.....	.....
24	89	7	96	3	1	×	.....	.....	.....	.....
25	87	8	95	4	1	.....	.....	.....	.....	.....
26	89	5	94	6	×	.....	.....	.....	.....	.....
27	85	12	97	3	×	.....	.....	.....	.....	.....
28	83	13	96	4	×	.....	.....	.....	.....	.....
29	85	10	95	4	1	.....	.....	.....	.....	.....
30	83	11	94	6	×	.....	.....	.....	.....	.....

Heavy mineral percentages of 30 samples of the Madison sandstone, Madison, Wis., taken at about 1-foot intervals and numbered consecutively from top to bottom. × denotes the presence of the mineral in quantities less than 1 per cent.

The Jordan sandstones vary from medium to fine grained. They are poorly cemented, range from well to poorly sorted, and have a yellow color on the outcrop. The thickness ranges from 20 to 40 feet. The Jordan has yielded no fossils and there is no positive evidence of marine origin; parts suggest deposition by wind. The Madison sandstone of the type region is fine grained at the top and is also more or less cemented by dolomite. The basal beds are poorly

cemented and resemble the Jordan. The color is yellowish gray to white. The thickness in an exposure near Madison in which both the top and bottom are shown is 39 feet. In places in western Wisconsin the beds at the top of the Jordan are cemented like those of the Madison which they closely resemble. Poorly preserved

TABLE II

Slide No.	Colorless Garnet	Pink Garnet	Total Garnet	Zircon	Tourmaline	Epidote	Location
100	72	6	78	12	10	.....	Middleton
101	74	8	82	12	6	×	.....
102	92	4	96	2	2	.....	.....
103	86	6	92	7	1	.....	.....
104	91	5	96	4	×	.....	.....
105	88	5	93	5	2	.....	.....
106	88	4	92	8	×	.....	.....
107	81	4	85	10	5	×	Cross Plains
108	86	6	90	8	2	.....	.....
109	85	6	91	8	1	.....	.....
110	90	4	94	5	1	.....	.....
111	85	5	90	10	×	.....	.....
112	84	7	91	6	2	.....	.....
113	85	6	91	8	1	.....	.....
114	89	3	92	6	2	×	.....
115	88	5	93	6	1	.....	.....
116	86	4	90	9	1	.....	.....

Heavy mineral percentages of 7 samples of the Madison sandstone, Middleton Wis., taken at 1-foot intervals and 10 samples from the Madison sandstone, Cross Plains, Wis., both numbered consecutively from top to bottom. × denotes the presence of the mineral in quantities less than 1 per cent.

marine fossils occur in the tops of these beds, but these may be a part of the lower beds of the succeeding Oneota.

THE MINERALS OF THE MADISON AND JORDAN SANDSTONES

The minerals that have been studied are divided into two groups, the "heavy" minerals and the "light" minerals. This division is based on the specific gravity of the minerals, those sinking in tetrabromoethane, specific gravity 2.90, being classed as heavy minerals, those floating in tetrabromoethane, as light minerals.

The percentage of the heavy minerals by weight in the sandstones is low, averaging about 0.3 per cent. The light grains are similar in all of the sections, the quartz grains making up by far the larger percentage with only a very small quantity of feldspar.

Garnet, both colorless and pink, zircon, and brownish tourmaline constitute the major percentage of the heavy minerals, and epidote and rutile are common to both, but not abundant in either. Other minerals are staurolite, cyanite, and anatase. These occur so rarely as to be of no significance.

TABLE III

Slide No.	Colorless Garnet	Pink Garnet	Total Garnet	Zircon	Tourmaline	Epidote	Cyanite
51	48	17	76	32	3	.....	.....
52	47	18	65	20	13	2	.....
53	50	19	69	25	4	×	.....
54	64	19	83	12	4	1	.....
55	48	12	60	8	32	.....	.....
56	56	22	78	15	6	1	.....
57	41	20	61	30	9	.....	.....
58	52	12	64	21	14	1	.....
59	62	18	80	10	10	.....	.....
60	66	19	85	7	7	1	.....
61	61	22	83	11	6	.....	.....
62	80	15	95	4	1	.....	.....
63	62	15	75	13	10	.....	.....
64	67	15	82	11	7	.....	.....
65	52	13	65	11	24	.....	.....
66	47	16	63	25	12	.....	.....
67	70	16	86	12	2	×	×
68	55	20	75	15	9	1	.....
69	61	20	81	15	4	.....	.....
70	41	18	59	22	18	1	.....
71	60	19	79	12	9	.....	.....
72	63	18	81	11	8	.....	.....
73	60	17	77	13	10	.....	.....
74	53	24	77	16	7	.....	.....
75	58	22	80	14	6	.....	.....

Heavy mineral percentages of 25 samples of the Jordan sandstone, Castle Rock, Sparta, Wis., taken at approximately 1-foot intervals and numbered consecutively from top to bottom. × denotes the presence of the mineral in quantities less than 1 per cent.

The relative percentages of the heavy minerals in the various sections are remarkably similar considering the distances of the sections from each other, and seem to indicate, as does the similarity of the mineral suites, a similar source and very similar conditions of deposition. Garnet persists with a very high percentage in all of the sections, averaging 90 per cent of the heavy minerals in the eastern Wisconsin sections and 75–85 per cent in the western Wisconsin sections. The zircon ranks second in the heavy mineral slides, being about 8 per cent in the Madison of eastern Wisconsin and 11–15

per cent in the Jordan of western Wisconsin. Tourmaline comes third in the list of important heavy minerals in all of the sections, the average percentage in the Madison of eastern Wisconsin being about 1 per cent and showing an increase to about 10 per cent in the western Wisconsin sections. The tourmaline shows its major in-

TABLE IV

Slide No.	Colorless Garnet	Pink Garnet	Total Garnet	Zircon	Tourmaline	Epidote	Rutile
76	47	18	65	25	10	.....	.....
77	49	23	72	20	8	.....	.....
78	53	19	72	22	6	×	.....
79	51	15	66	28	6	.....	.....
80	39	12	51	14	35	.....	.....
81	52	13	65	23	12	×	.....
82	52	20	72	18	10	.....	.....
83	34	6	40	35	24	.....	1
84	58	21	79	12	8	1	.....
85	58	21	79	12	8	1	.....
86	62	18	80	15	5	.....	.....
87	68	13	81	15	3	1	.....
88	57	13	70	14	16	.....	×
89	70	15	85	10	5	.....	.....
90	72	18	90	8	2	.....	.....
91	70	18	88	11	1	.....	.....
92	72	13	85	13	2	.....	.....
93	71	16	86	12	2	.....	.....
94	70	13	83	16	1	.....	.....
95	71	14	85	12	3	.....	.....
96	74	13	87	12	1	.....	.....
97	68	20	88	11	.....	.....	.....

Heavy mineral percentages of 21 samples of the Jordan sandstone, La Crosse, Wis., taken at approximately 1-foot intervals and numbered consecutively from top to bottom. × denotes the presence of the mineral in quantities less than 1 per cent.

crease in thin layers of the formations and is not constant in its percentages. It is interesting to note that the so-called Madison lying above the Jordan in the western sections varies more from the Madison of the eastern sections in heavy mineral content than does the Jordan below.

The physical characteristics of the minerals in the various sections are essentially the same. The garnet is coarse and angular with a characteristic hackly surface in all of the slides. Some slides show a few garnets that are subround but they are never in abundance. The zircon maintains its small, rounded character throughout and the tourmaline occurs persistently as rounded, brownish grains. This

similarity of the physical characteristics, however, is not as significant as in the case of the less durable minerals, for these latter would reflect variations in conditions of source, transportation, and deposition much better than would the former.

The following tables show the percentages of the heavy minerals in the samples of the Madison sandstone from Madison, Middleton, and Cross Plains, and of the Jordan sandstone from La Crosse, Sparta, etc. The tables show the analyses of samples taken at approximately 1-foot intervals in the various sections and give the relative percentages of the heavy minerals obtained by separation with heavy liquid. Minerals present in quantities less than 1 per cent are indicated by a cross.

SOURCE OF THE MATERIALS OF THE MADISON AND JORDAN SANDSTONES

The heavy minerals of the Madison and Jordan sandstones suggest that the composing sediments were derived from the re-working of older sediments and not directly from crystalline rocks. As noted above, the sandstones are composed of quartz, a little feldspar, and several heavy minerals, the latter being garnet, zircon, and tourmaline, all of which are minerals of high chemical stability. Milner[1] states that the presence and the predominance of zircon, tourmaline, rutile, and iron ores to the exclusion of other species implies a derivation from pre-existing sediments, and the location of the source is made difficult. It can be seen that the small variety of heavy minerals and the predominance of the stable ones in the Madison and Jordan sandstones are indicative of either a very remote source or the re-working of a pre-existing sedimentary formation, the latter seeming more probable. The aforementioned facts and the roundness of the zircon and tourmaline seem to indicate that the constituents of the Madison-Jordan formation have gone through more than one cycle of erosion.

COMPARISON OF THE MADISON-JORDAN SANDSTONES WITH OTHER CAMBRIAN FORMATIONS

Table V shows the results of some analyses of sandstones from Cambrian formations other than the Madison and Jordan, and

[1] H. B. Milner, *Introduction to Sedimentary Petrography* (1921).

indicates that the latter horizon may be easily distinguished from the St. Lawrence, Franconia, and Dresbach sandstones by means of the heavy mineral contents of the different formations. The high percentage of garnet in the Madison-Jordan formation permits its ready identification. The preliminary studies seem to indicate that the St. Lawrence formation is characterized by a dominance of zircon and tourmaline in its heavy minerals, that the Franconia

TABLE V

COMPARATIVE TABLE SHOWING THE PERCENTAGES OF HEAVY MINERALS IN THE MADISON, ST. LAWRENCE, FRANCONIA, AND DRESBACH SANDSTONES

	Garnet	Zircon	Tourmaline	Epidote	Rutile	Anatase	Opaque (Ferruginous)
Madison	90	8	2	×	×	.....	.....
St. Lawrence	×	76	22	2	.....	×	.....
Franconia	15	3	8	.....	.....	.....	74
Dresbach	25	60	15	.....	.....	.....	.....

contains few heavy minerals other than those which are iron bearing and opaque, and the Dresbach has zircon as its dominant heavy mineral, but garnet and tourmaline are important. Further studies are necessary before it can be stated that the foregoing statements have general application.

CONCLUSIONS

The mineral constituents and their characteristics strongly suggest that the Madison sandstone and the Jordan sandstone are not two formations but are one and the same formation, the western phase deposited in a slightly different environment from the eastern.

The comparison of the heavy minerals of the Madison-Jordan formation with those of the St. Lawrence, Franconia, and Dresbach sandstones seems to indicate that they may be readily differentiated from each other by this means.

MAJOR TIME-DIVISIONS SINCE THE PRE-CAMBRIAN

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ABSTRACT

A summary of the terminology for the major elements of geologic time since the beginning of the Cambrian is given, with the present standing of those terms in modern usage. It is proposed to combine the Mesozoic and Cenozoic into a single era, the Neozoic, and to divide the Paleozoic into two eras, Eo-Paleozoic and Neo-Paleozoic. The name "Metazoic" is also suggested as a collective term for all time since the pre-Cambrian.

In the study of earth history, time since the pre-Cambrian is conveniently divided into eras on the basis of life-development: thus Paleozoic (ancient life), Mesozoic (medieval life), and Cenozoic (modern life). These larger divisions or eras are furthermore separated into geologic periods, and the periods in turn into epochs. The present standard of classification has been used for nearly ninety years, and is becoming fixed in geologic literature.

In the light of recent appreciation of the time durations involved, it is apparent that the individual eras or stages of life-development as now used do not include equivalent time durations, and the question can well be raised whether it would be either possible or advisable to rearrange the geologic periods in such a fashion as to represent better the changes of life-development during equal intervals of time. The present article will attempt to point out the history of the current classification, and will propose the consideration of a modification along lines suggested in the foregoing, bringing the matter up for general comment and criticism. The first point to be considered is the development of the present standard classification which is commonly called the "zoic scheme."

By common consent, the accepted terminology of the major units of geologic time includes only those terms ending in -zoic, from *zoe*, the Greek term for *life*. This scheme had its initiation in Sedgwick's word "Paleozoic," and was followed by Phillips and adopted by later authors. Its merit for those eras from which life-groups have been

recognized is obvious: its use for the unfossiliferous pre-Cambrian eras is subject to some criticism. Over twenty zoic terms have been applied by various authors to different larger divisions of geologic time. For the pre-Cambrian eras, collectively or separately, the following terms have been proposed:

AGNOTOZOIC, Irving 1887, unknown life.
ARCHEOZOIC, Dana 1872, archaic life.
AZOIC, Murchison *et al.* 1845, without life.
COLLOZOIC, Lane 1917, protoplasmic life.
EOZOIC, Dawson 1868, dawn of life.
HYPOZOIC, Phillips 1855, beneath or before life.
PAMPALEOZOIC, Gregory and Barrett 1927, primeval life.
PROGNOZOIC, Sederholm 1914, ancestral life.
PROTEROZOIC, Emmons 1888, earlier life.
PROTOZOIC, Sedgwick 1838, early life.
PROZOIC, Phillips 1885, before life.

For time since the pre-Cambrian, the following zoic terms have been suggested:

CENOZOIC, Phillips 1840, recent or modern life.
DEUTEROZOIC, Lapworth and Page 1888, second life.
DEUTOZOIC, Lapworth and Page 1899, second life.
EOPALEOZOIC, Dana 1894, early ancient life.
MESOZOIC, Phillips 1840, medieval life.
NEOPALEOZOIC, Dana 1894, late ancient life.
NEOZOIC, Forbes 1854, new or late life.
PALEOZOIC, Sedgwick 1835, ancient life.
PROTEROZOIC, Lapworth 1888, earlier life.
PROTOZOIC, Lapworth 1888, early life.
PSYCHOZOIC, LeConte 1877, reasoning life.

Other terms not of the zoic type have been proposed for the larger subdivisions of the pre-Cambrian. The more important of these are:

ALGONKIAN, Walcott 1889.
ARCHEAN, Dana 1872.
EOBIOTIC, Hitchcock 1888.
EOMORPHIC, Hitchcock 1888.
PROGONIC, Sederholm 1914.

The persistent use of terms of the zoic type has resulted in the nearly universal abandonment of such terms as do not conform to this type, so that most of these other terms have dropped into disuse.

The present article deals only with the division of time since the pre-Cambrian, and the terminology of earlier geologic time will not be here discussed. Two recent articles[1] have carefully discussed the pre-Cambrian nomenclature.

The term "Paleozoic" was first introduced by Sedgwick[2] in 1838, who described it as including the periods, or systems, which are now called Cambrian, Ordovician, and Silurian. He specifically stated that overlying this "series" came the Old Red sandstone (Devonian), so that by original definition the Paleozoic contained only the three systems mentioned in the foregoing. Two years later in an obscure publication, Phillips[3] proposed the addition of the Old Red sandstone, or Devonian, series to the Paleozoic group, and suggested, although not formally, that the Carboniferous be added also. (The Carboniferous here mentioned did not include the Permian.) In 1841 Phillips[4] definitely added the Carboniferous and, for the first time, the Magnesian limestone (Permian). A few years later, the work of Murchison, Keyserling, and De Verneuil on the Permian beds of Russia established the Permian age of the lower part of the New Red sandstone, which thereby became added to the Paleozoic group. With these additions, the original Paleozoic as proposed by Sedgwick became expanded to the limits within which it is commonly accepted at the present time.

Since 1845, however, there have been a number of suggested changes in the content of the Paleozoic era, none of which has been widely accepted. In Phillips' *Manual of Geology*, Part II, edited by Etheridge (1885), the Paleozoic is divided into three smaller groups, the lowest of which includes Silurian, Cambrian, and Laurentian. The Laurentian, furthermore, is defined as containing, among other formations, the Adirondack anorthosite of New York and the horizon of Eozoon (Grenville). Thus, by the original author of the term,

[1] J. W. Gregory and B. H. Barrett, "The Major Terms of the Pre-Paleozoic," *Jour. Geol.*, Vol. XXXV (1927), pp. 734–42; M. Grace Wilmarth, "The Geologic Time Classification of the U.S. Geological Survey Compared with Other Classifications," *U.S. Geol. Survey Bull. 769 (1925)*.

[2] Adam Sedgwick, *Geol. Society of London Proceedings*, Vol. II, No. 58 (1838), pp. 684–85.

[3] *The Penny Cyclopedia*, Vol. XVII (1840), pp. 153–54.

[4] *Gt. Britain Geol. Survey Mem.* (1841), p. 160.

the lower limit of the Paleozoic was extended to include no inconsiderable part of the present pre-Cambrian. A modification of this same extension was much later offered in 1913[1] and 1916[2] by Lawson, who suggested the inclusion in the Paleozoic of the Algonkian period and system, which he defined as including Keweenawan and Animikian "epochs." In 1909, Schuchert[3] made the suggestion that the term "Paleozoic" be restricted to the Cambrian and Ordovician periods collectively, excluding from it the later periods. In his 'Revision of the Paleozoic Systems,"[4] Ulrich proposed to transfer the Permian and Pennsylvanian systems from the Paleozoic to the Mesozoic era, abandoning the term "Permian" entirely for North American geology, and apportioning its horizons between the Pennsylvanian and Triassic systems. None of these proposed changes has been generally accepted, and while numerous other suggestions have been made for redividing the time and rock units within the Paleozoic, no further changes of importance have been proposed for its limiting boundaries.

Although the term "Proterozoic" signifies upper or late pre-Cambrian in American geological literature, its use in Great Britain for the Lower Paleozoic necessitates a discussion at this point of the history of the term. Proterozoic first appears in print in a letter from S. F. Emmons to Persifor Fraser under date of May 25, 1887, and published in 1888.[5] The original application given by Emmons at this time was to the rock formations which intervene between the Archean and the Cambrian, i.e., the upper or late pre-Cambrian. An independent application of the same term was printed in the same publication[6] and made by Lapworth. He suggested the use of the term "Proterozoic" for the lower "grand life-period" of the Paleozoic, and defined it as including the Cambrian, Ordovician, and Silurian

[1] A. C. Lawson, "A Standard Scale for the Pre-Cambrian Rocks of North America," *Inter. Geol. Congress*, Vol. XII (1913), p. 370.

[2] A. C. Lawson, "The Correlation of the Pre-Cambrian Rocks of the Region of the Great Lakes," *Calif. Univ., Department of Geol., Bull. 10*, No. 1 (1916), chart opp. p. 18.

[3] Charles Schuchert, "Paleogeography of North America," *Geol. Society of America Bull.*, Vol. XX (1910), pp. 515, 606.

[4] E. O. Ulrich, *Geol. Society of America Bull.*, Vol. XXIII (1911).

[5] "American Committee Reports," *Inter. Geol. Congress*, Vol. IV (1888), p. A71.

[6] C. Lapworth, *Inter. Geol. Congress*, Vol. IV (1888), p. 222.

periods. It has lately been established[1] that Lapworth was using this application of "Proterozoic" in his lectures as early as 1886. Thus, there are two distinct definitions of "Proterozoic" dating back to 1888, and from this fact has arisen some confusion. Emmons' use of the term was not widely adopted until 1906, when it was sponsored by Chamberlin and Salisbury in their famous textbook, since which time it has become widely accepted in North America for the latter part of the pre-Cambrian. Lapworth's use of the term gradually spread among certain British geologists and was used to some extent both prior to 1906 and since that time. It is still in slight use at the present time. Of the two applications of the term "Proterozoic," that of Emmons' has the priority of published designation, while that of Lapworth has the priority of usage. The use of "Proterozoic" for the late pre-Cambrian, as suggested by Emmons, has the sanction of general acceptance by the majority of authors.

The term "Mesozoic" was first coined by Phillips[2] in 1840, but at this time no definition of its application was given. The next year, however, Phillips[3] defined the term to include the Cretaceous, Oolitic (Jurassic), and the New Red sandstone (then Triassic and Permian). Shortly afterward, the lower part of the New Red sandstone was recognized as of Permian age, and so was excluded from the Mesozoic which then took on its present connotation.

The word "Cenozoic" (variously spelled Kainozoic, Cainozoic, etc.) was first suggested in 1840 by Phillips[4] as a possible term to use in naming a division of geologic time, and later, in 1841,[5] he definitely proposed its application to geologic time since the Mesozoic.

In his presidential address before the Geological Society of London in 1854, Edward Forbes[6] made what Lapworth afterward described as a "brilliant generalization," by remarking that life after the Paleozoic era was so very different from life during that era, that the time since the Paleozoic could well be considered a single era and

[1] Gregory and Barrett, *op. cit.*, p. 737.

[2] J. Phillips, *The Penny Cyclopedia*, Vol. XVII (1840), pp. 153–54.

[3] *Great Britain Geol. Survey Mem.* (1841), p. 160.

[4] *The Penny Cyclopedia, loc. cit.*

[5] *Great Britain Geol. Survey Mem., loc. cit.*

[6] *Proc. Geol. Society of London*, Vol. X (1854), p. lxxix.

might be called the "Neozoic" era. This suggestion to include the Mesozoic and Cenozoic in a single era has never been given much consideration, yet it is one of the contentions of the present article that the suggestion contains much of merit, and should be reconsidered in the light of present geologic studies. Lyell[1] and Jukes-Browne[2] used "Neozoic" in their textbooks, but no other writers of the time adopted the term and it has largely been dropped from current geologic literature, although it may be found in Fay's *Glossary of the Mining and Mineral Industry*, published in 1920. Schuchert,[3] in 1909, without comment on the earlier application, proposed that "Neozoic" be used as a synonym of Tertiary, but later abandoned this suggestion, and the name does not now appear in his *Textbook of Historical Geology* (1925). A similar adaptation of the term had been used by De Lapparent in his textbook of 1906.

It has long been recognized that the Paleozoic era may be divided into two smaller units without loss of the general relationships, and with considerable gain in matters of convenience. This is especially true in view of the fact that the Paleozoic was a very long duration of time, much longer than either of the later eras.

In 1888, at the Fourth International Geologic Congress, the Committee assigned to the Lower Paleozoic defined that term as including Cambrian, Ordovician, and Silurian. At this same meeting, Marr[4] suggested the term "Barrandian" for these three periods collectively, but the name was never adopted. Later on the same day, Lapworth[5] suggested "Proterozoic" for the same sequence, and as a possible substitute, the term "Protozoic." He renewed this suggestion in Page's *Textbook of Geology* (edited by Lapworth) in 1888 and in 1899. As has already been mentioned, "Proterozoic" had been earlier designated by Emmons for a pre-Cambrian sequence, and in a similar manner, "Protozoic" had likewise been preoccupied by use for pre-Cambrian rocks (wholly or in part) as suggested by

[1] Charles Lyell, *Manual of Elementary Geology* (1855), p. 407.

[2] A. J. Jukes-Browne, *Handbook of Historical Geology* (1886), p. 257.

[3] Charles Schuchert, *op. cit.*, pp. 515, 606.

[4] J. E. Marr, *Inter. Geol. Congress*, Vol. IV (1888), pp. 221–22.

[5] C. Lapworth, *op. cit.*, p. 222.

Sedgwick[1] in 1838. The use by some authors of the term "Eo-Paleozoic" for these three periods should be noted.

The division of the Paleozoic into two suberas as proposed by Dana[2] in 1894 restricted only the Cambrian and Ordovician to the Lower Paleozoic, which he called the "Eo-Paleozoic" section. This separation of the two lower Paleozoic systems from the five upper systems has been followed by the majority of authors who use the terms "Eo-Paleozoic" and "Neo-Paleozoic," and is a more logical division than that which includes the Silurian with the two early systems. For the time and rock series included between the top of the Silurian and the beginning of the Mesozoic, Lapworth (in editing Page's *Textbook of Geology* in 1888 and 1899) proposed the term "Deuterozoic" or "Deutozoic." Neither of these terms, however, has gained currency in geologic literature. For the more logical Upper Paleozoic, and including the Silurian, Devonian, and Carboniferous systems, Dana suggested the name "Neo-Paleozoic," a term which has commonly been used for that sequence.

From the many comments of beginning students of historical geology, it has been brought to the attention of the writer that even the casual student of earth history appreciates the discrepancy in time duration between the present geologic eras. The Paleozoic era embraces something like 430 million years; the Mesozoic era about 155 million years; and the Cenozoic about 60 million years—roughly a ratio of about $7 : 2\frac{1}{2} : 1$. As outlined in the foregoing, the zoic system of nomenclature is based upon the progressive development of life as implied by the translation of the era terms, "ancient," "medieval," and "modern" life. It is thus apparent when the time values are given to these evolutionary divisions that the time of ancient life was 7 units long; of medieval life, $2\frac{1}{2}$ units; and of modern life, 1 unit. This apportionment would further imply either that an equal amount of life-development is not included in each era, or that development was much slower during the Paleozoic, and has progressively hastened during succeeding eras.

It should be possible to apportion geologic time since the pre-Cambrian in more equal divisions without great loss in the present

[1] Adam Sedgwick, *op. cit.*, p. 684.

[2] J. D. Dana, *Manual of Geology* (4th edition, 1894), p. 460.

connotations or the era names and without great confusion. Furthermore, it seems as if such a change could be made so that the new divisions would be comparable in life-development and physical history as well as in duration. The writer would like to propose for consideration and criticism the following modification of the major time divisions since the beginning of the Cambrian.

The present time values of the Paleozoic, Mesozoic, and Cenozoic are 7, $2\frac{1}{2}$, 1 units of time, respectively. If the Mesozoic and Cenozoic eras be taken together and called the "Neozoic" era—as was long ago proposed by Forbes— their combined ratio of $3\frac{1}{2}$ units of time would be exactly one-half that of the Paleozoic era. Further, if the Paleozoic be separated into two smaller divisions of equal duration, there would then be three major time-divisions of equal length, the early Paleozoic, the late Paleozoic, and the Neozoic. If the current names for these Paleozoic subdivisions be used, these three eras would then be Eo-Paleozoic, Neo-Paleozoic, and Neozoic. The Eo-Paleozoic would include the Cambrian and Ordovician; the Neo-Paleozoic, the Silurian and Devono-Carboniferous periods; and the Neozoic all post-Permian time.

This proposed modification involves no difficult change, and it may very well make for a much more logical division of time, with little attendant confusion or loss of convenience in its adoption. Three steps are essential in establishing the proposed change. The first is to revive the term "Neozoic" for the Mesozoic and Cenozoic eras collectively. This word, strangely enough, has never been widely accepted despite its appropriateness. It conforms to the zoic scheme, has a proper application, and is extremely convenient for use in referring to post-Paleozoic time. The second step calls for an acceptance of the Eo-Paleozoic and Neo-Paleozoic as full-fledged eras. This is rational on the ground that each of these units represents as much time duration, life-development, and variety of diastrophic change as does the whole of the Neozoic, or Mesozoic and Cenozoic combined. The third step involves the current use of these suggestions in geologic literature and is, of course, the most difficult of all three steps to be sanctioned.

This proposed classification will undoubtedly be strongly criticized on the ground that the present time-divisions are so well es-

tablished that it is not feasible to change them. Priority should play an important part in all nomenclature, and it is reasonable that since the present classification has for so long been current, no change should be made without careful consideration, not only of the importance of the suggested change, but also of the amount of confusion which would thereby be caused. None of the proposed terms is new in form, novel in application, or obscure in meaning, and the composite suggestion is neither difficult to adopt nor confusing to use. Possibly the time is not ripe for standardization of the geologic time-scale. It may well be that it is too early in the development of geologic science for permanent, ultimate standards of classification to be established. Surely, it is not too late for consideration of changes in our present and probably transitionary classifications, when the prospect of improvements may be in view. Under any circumstances constructive criticism is a healthy medium of progress, and it is quite possible that discussion of the suggestions herein raised may lead toward betterment of the geologic time classification along lines which might otherwise have been neglected.

Similarities between the three proposed eras are striking. Each is ended by a "revolution" or major period of diastrophic unrest, and each contains at least four lesser periods of crustal disturbance similarly spaced in the time-division. Since these critical periods of orogeny radically modify the general aspect of the physical environment, it is to be expected and may be observed that such features as climate, invasion by epeiric seas, sedimentation, and to some extent vulcanism are likewise similar for the three eras, and that at corresponding times in each division similar environmental conditions prevailed. Furthermore, in each of these proposed eras, a major life-group passes through its early stages of development, invades the next higher type of environment, reaches its culmination of development, and begins to decline. Thus the Eo-Paleozoic is the time of invertebrates; the Neo-Paleozoic the time of the lower vertebrates; and the Neozoic, the time of the higher vertebrates. With the fulness of invertebrates in the Middle and Upper Ordovician, of the amphibia and ancient reptiles in the Upper Carboniferous, and of the dinosaurs and mammals in the Cretaceous and Tertiary, each of the major life-divisions reaches its supremacy during approximately

the same part of the great time-divisions, giving a more balanced apportionment of time to the life-groups than is evident with the present grouping of time units. The writer is well aware that the comparisons which have here been stressed may be somewhat offset by contrasts, and that he may be accused of emphasizing the similarities to further his position. That there are similarities, however, cannot be denied, and the writer feels that they are of sufficient importance to justify consideration of the suggested changes in the standard classification.

The opportunity to point out the lack of a needed term in geologic chronology should not be overlooked. This need is for some term to use for all time since the pre-Cambrian; in other words, for some term to embrace the Paleozoic and Neozoic eras collectively. The nearest approach to such a term is "post-Proterozoic," which possibly is objectionable because of the dual meaning of Proterozoic already alluded to. The needed term should be a zoic term, and should bring out the significance of the higher and more developed life of the Paleozoic and Neozoic eras as compared to that of the pre-Cambrian. It is possible that the word "Metazoic" would fill this need. Since the time under consideration is characterized by animals higher than protozoa, and since the name "metazoa" is commonly applied to such animals in zoölogy, "Metazoic" could be applied to the time of their abundance without serious difficulty. To be considered with the other suggestions made in this article, the term "Metazoic" is proposed for all time since the beginning of the Cambrian. It would therefore include three eras, Eo-Paleozoic, Neo-Paleozoic, and Neozoic.

THE MOYIE-LENIA OVERTHRUST FAULT

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ABSTRACT

Five distinct faults described by various earlier workers were recognized as parts of one great overthrust fault in the field seasons of 1924 and 1925. This fault extends from Kootenay[1] River in Canada to Clark Fork River in Montana, a distance of 118 miles. It has been named the Moyie-Lenia overthrust fault. The fault plane dips west. The vertical stratigraphic interval may be more than 45,000 feet at some places, but it may be as low as 15,000 feet at others. There is no evidence that the overthrust displacement is greater than the vertical displacement. The age of the overthrust was probably post-Jurassic and pre-Eocene, and it it is believed to be part of the great overthrust system known to exist farther south.

INTRODUCTION

Calkins and MacDonald,[2] so far as is known, were the first geologists of the United States to recognize any part of this great structural feature. Their field work for the United States Geological Survey was done in the summer of 1905. Daly,[3] a Canadian Survey worker, in the 1904 field season had observed about 5 miles of a fault crossing the International Boundary, which his maps, published subsequently, show to be a part of this overthrust fault. Daly did not give his small segment of this fault a name; and, as shown by his later published maps and structure sections, it was recognized by him as only an undistinguished one of several normal faults which crossed the International Boundary in the 45-mile strip across northern Idaho.

Calkins and MacDonald[4] observed a part of this fault for about 26 miles of its length, in Idaho and Montana, and named it the Lenia fault, from a railway station situated on the south side of the Kootenai River in Idaho, a few hundred yards from the Idaho-Montana state line. Its southeastern extremity they traced to a

[1] Spelled "Kootenay" in Canada and "Kootenai" in the United States.

[2] F. C. Calkins and D. F. MacDonald, "A Geological Reconnaissance in Northern Idaho and Northwestern Montana," *U.S. Geol. Survey Bull. 384* (1909).

[3] R. A. Daly, "Geology of the Western Part of the International Boundary," *Summary Rept. of Geol. Survey of Canada for 1904, 1905*, pp. 91–100.

[4] *Op. cit.*

point near the wide alluvial-covered valley of Lake Creek, which flows north to Kootenai River. They included the short fault segment mapped by Daly on their reconnaissance map, but apparently did not realize its relation to the Lenia fault. It was still unnamed and was not mentioned in the text.

During the same field season Calkins and MacDonald[1] also recognized and mapped another fault, which they named the Bull Lake fault. This lies a little more than 2 miles east of Bull Lake and Lake Creek which drains it. This fault they observed and mapped for a distance of about 10 miles.

Another fault, unnamed, was observed and mapped for a distance of about 9 miles. It was located west of Bull River and was traced from Kootenai River on the south to the alluvial-covered basin, in which Bull Lake lies, to the north.

Marius R. Campbell *et al*[2] in a publication of 1915

[1] *Op. cit.*

[2] Marius R. Campbell *et al.*, "Guidebook of the Western United States. Part A, The Northern Pacific Route," *U.S. Geol. Survey Bull. 611*, Sheet 20 (1915).

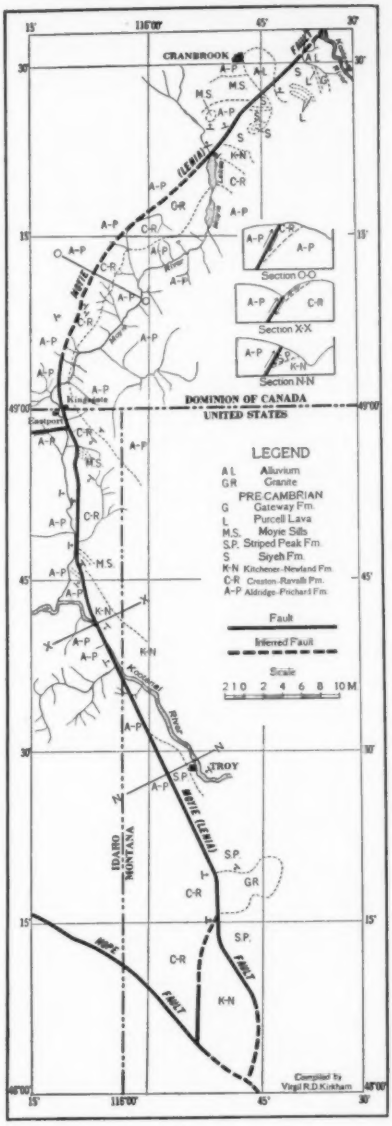

FIG. 1

shows about 10 miles of this latter fault. It intersects the Hope fault about 3 miles west of the mouth of Bull River. On the same map is shown about 5 miles of the Bull Lake fault, mapped by Calkins and MacDonald.[1]

Results of field work of 1909–13 in the Cranbrook area of British Columbia by Stuart J. Schofield,[2] of the Canadian Survey, were published in 1915. On his Map 147 A, he shows the small segment of fault mapped by Daly[3] at the International Boundary Line to extend for 46 miles in British Columbia northeastward to the alluvium-filled structural valley of the Kootenay River east of Cranbrook. This he named the Moyie fault.

Daly's maps of the International Boundary Survey had been published[4] by this time, and repeated his conclusions as reported in his earlier progress reports.

The writer's work[5] in 1924 and 1925 showed that the short segment recognized at the boundary in 1904 by Daly, and the Lenia fault mapped by Calkins and MacDonald[6] in 1905, are parts of one fault which extends along the Moyie River in Idaho.

Field work in 1925 and at later dates showed the Bull Lake fault to be connected with the Lenia fault, and furnished persuasive evidence for believing that the fault west of Bull River is a small branch of the much larger and more extensive fault to the east.

The fault, which extends for 46 miles in Canada, and which lies near the Moyie River for most of that distance, enters Idaho at Eastport and continues with the Moyie River for another 20 miles before joining the Kootenai River, which it follows up stream, as the Lenia

[1] *Op. cit.*

[2] "Geology of the Cranbrook Map-Area, British Columbia," *Canada Geol. Survey Memoir 76* (Ottawa, 1915).

[3] *Op. cit.*

[4] Reginald A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Canada Dept. Interior, Rept. of Chief Astronomer for 1910*, Vols. II and III, pp. 1–799; Map 1913 also issued as *Canada Geol. Survey Memoir 38* (Ottawa, 1915).

[5] Virgil R. D. Kirkham and Ernest W. Ellis, "Press Bulletin on Geology and Mineral Resources of Boundary County, Idaho," *Idaho Bur. of Mines and Geol. Press Bull. 12* (December, 1924); "Geology and Ore Deposits of Boundary County, Idaho," *Idaho Bur. of Mines and Geol. Bull. 10* (November, 1926).

[6] *Op. cit.*

fault of Calkins[1] for 26 miles. From here it was traced for 7 miles, by the writer, to where it joins the Bull Lake fault of Calkins,[2] which was in turn traced by the writer to its intersection with the Hope fault.

MAGNITUDE OF THE MOYIE-LENIA FAULT

The fault, which is now known to extend 118 miles, has been traced continuously from the Kootenay River in Canada to the Clark Ford River in Montana. Its length in British Columbia is more than 46 miles, in Idaho 28 miles, and in Montana 44 miles. The fault, as now recognized, includes five segments formerly described as separate faults.

Inasmuch as the largest single segment of 46 miles was called the Moyie fault by Schofield,[3] and 20 additional miles along the Moyie River was recognized by the writer in 1924,[4] the writer called the new reconstructed fault the Moyie (Lenia) fault in the report[5] of 1926. The name Moyie-Lenia overthrust fault is here proposed as a suitable name for this extensive structural feature, and it will be thus referred to in the rest of this paper.

DESCRIPTION OF MOYIE-LENIA FAULT

Daly,[6] who was probably the first worker to recognize any part of the fault, believed it to be normal where he observed it for 5 miles at the International Boundary.

Calkins[7] showed, on his map, the same segment with the downthrow on the east. He showed Burke, Revett, and St. Regis (included in Creston-Ravalli on map) lying on both sides of the fault. He failed to describe the fault in his text, and it is not known whether he considered it as belonging to the normal or to the reverse type.

Calkins,[8] in describing the Lenia fault, showed, on his map, the downthrow of this also to be on the east and said in the text on page 53, "It has a steep dip, whose direction is not certainly known,

[1] *Op. cit.* [2] *Op. cit.* [3] *Op. cit.*

[4] *Idaho Bur. of Mines and Geol. Press Bull. 12.*

[5] *Idaho Bur. of Mines and Geol. Bull. 10*, pp. 34–35 and Plate III.

[6] Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Canada Dept. Interior Rept. of Chief Astronomer for 1910*, Vols. II and III, pp. 1–799.

[7] *Op. cit.* [8] *Ibid.*

and the downthrow is on the east." On page 54, he said, "There is intense disturbance and crushing for some yards on either side of the fissure, which seems to be nearly vertical." Also on page 54, he said,

> The promising "Big Eight" and "B. and B." mines on this stream, in slates and quartzitic sandstones of the Prichard formation west of the fault are located on fissures whose course is about parallel to this great dislocation and which dip steeply to the west. The suggestion arises that the Lenia fault may be of the steep reversed type.

In describing the Bull Lake fault on page 55, he said,

> It is an overthrust dipping 45 degrees W. The force which produced it produced also a strong and extensive schistosity in the granite east of it, and intensely sheared and crumpled the sedimentary rocks in its vicinity farther south.

On page 67 he said, concerning this,

> The tremendous pressure necessary to have sheared the rock so thoroughly can hardly be accounted for by friction evolved in normal faulting on a plane of 45° dip, but it might have been produced by the great tangential compressive strain involved in the production of a reversed fault. Additional evidence bearing on this matter, and striking proof of intense dynamic action, are observed in line with this fault at the forks of Bull River southeast of the lake. At the foot of the spur between the forks there are outcrops of sedimentary rock so intricately crumpled and so greatly altered that at first sight they were taken to belong to a pre-Algonkian complex. The minute folds were found to be recumbent toward the east, which should be the case if they were produced by overthrusting from the west. To the east, however, these intensely deformed rocks pass gradually into regularly dipping beds resembling the Newland.

On page 68 he said,

> It was inferred from these relations that the Newland on the west was thrust by this fault against similar beds on the east younger than the Striped Peak. . . . . Thus stratigraphic as well as structural evidence indicates an overthrust dipping to the west.

In describing the fault west of Bull River, Calkins[1] said,

> This fault was observed in a gulch west of a point at about the middle of Bull River Valley. Here are exposed purple and green shales of the St. Regis formation overlain by typical Lower Newland beds, dipping gently to the east and abutting against brecciated white quartzite. The plane of contact appears to dip steeply west, which would imply reverse faulting, but this could not be proved without more thorough examination.

[1] *Ibid.*, p. 65.

In describing the Moyie fault in Canada, Schofield[1] said,

> The second great movement which affected the Purcell Range was normal faulting, a northeast-southwest system, including the Marysville and Moyie faults and several small faults of lesser importance.

Nothing more is said in his text about the relations of this fault, nor does he at any place state the direction of dip of the fault plane or the downthrow side. Curiously enough, Schofield[2] contradicts himself on his Map 147 A, which accompanies his report, by showing in the two structure sections which cross the Moyie fault along line *A-B* and along the International Boundary, that the fault plane dips to the west. He showed there also, by arrows indicating direction of movement, that the fault is a high-angle thrust from the west. The writer[3] in 1924 and 1926 described the Moyie and Lenia faults and the hitherto unrecognized fault connecting them as an overthrust from the west.

At the time when Daly[4] and Calkins[5] wrote of their reconnaissances in this region, many great overthrusts from the west, such as the Bannock[6] in the Rocky Mountains to the south, were unknown. It was not until a much later date that overthrusts of great horizontal and lineal extent were accepted generally as of common occurrence in this region.

It seems likely that the same field work, if done in the light of present ideas, would result in the unanimous recognition of the over-

[1] *Op. cit.*, p. 93. [2] *Op. cit.*

[3] *Idaho Bur. of Mines and Geol. Press Bull. 12* and *Idaho Bur. of Mines and Geol. Bull. 10.*

[4] Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Canada Dept. Interior Rept. of Chief Astronomer for 1910*, Vols. II and III, pp. 1–799.

[5] *Op. cit.*

[6] R. W. Richards and G. R. Mansfield, "The Bannock Overthrust, A Major Fault in Southeastern Idaho and Northeastern Utah," *Jour. Geol.*, Vol. XX (1912), pp. 681–707. G. R. Mansfield, "Types of Rocky Mountain Structure in Southeastern Idaho," *ibid.*, Vol. XXIX (1921), No. 5, pp. 444–68; "Structure of the Rocky Mountains in Idaho and Montana," *Geol. Soc. of Amer. Bull.*, Vol. XXXIV (1923), pp. 263–84. Virgil R. D. Kirkham, "Geology and Oil Possibilities of Bingham, Bonneville, and Caribou Counties, Idaho," *Idaho Bur. of Mines and Geol. Bull. 8*, pp. 31–33, 88, 89, 103–5 (September, 1924); "A Geologic Reconnaissance of Clark and Jefferson and Parts of Butte, Custer, Fremont, Lemhi and Madison Counties, Idaho," *Idaho Bur. of Mines and Geol.*, Pamphlet 19, pp. 26–27 (January, 1927).

thrust relationships. The writer has examined all of these faults and finds the overthrust character of each of these segments to be amply proved by field evidence. There is no reasonable doubt that one overthrust fault of great magnitude extends without interruption from Kootenay River in Canada to Clark Fork River in Montana, as shown on the accompanying map.

Except for a distance of 25 miles on the south, the rocks on the western and overthrust lip of the fault are now known to be made up of one formation. This is the basal Aldridge-Prichard[1] (see legend on map) formation and its included sills of the Belt (Purcell) series of pre-Cambrian age.

To the west of the western branch, at the south end of the fault, lies the Creston-Ravalli formation. This formation overlies the Aldridge-Prichard conformably and is thrust to the east over the younger Kitchener-Newland, which is in turn thrust to the east, in the eastern branches of the fault, over younger Striped Peak and later beds.

The area east of the fault is structurally a great anticlinal arch in competent beds. Truncation by erosion reveals Aldridge-Prichard as the core with bands of overlying Creston-Ravalli on its flanks.

The Creston-Ravalli is overlain, in turn, on the south by the Striped Peak formation and on the north by the Siyeh formation. No Siyeh is known in the southern area and no Striped Peak is known in the northern area. The absence of one at each locality can be accounted for by (1) lack of deposition, (2) deposition and then removal by erosion before the deposition of succeeding sediments, or (3) conditions of sedimentations which changed in such a manner that shales were being deposited to the south while coarser materials were being deposited to the north. In this latter circumstance the Siyeh and Striped Peak formations may be in some part contemporaneous.

To the north, interbedded with the Siyeh formation, are several thick lava flows which end abruptly against the fault trace on the west. The Gateway formation (youngest Belt) lies on the east side of the fault and farthest north next to the Kootenay River. At this

[1] See pages 15–27 of *Idaho Bur. of Mines and Geol. Bull. 10* for stratigraphy and correlation too bulky to reproduce here.

locality the Aldridge-Prichard (oldest Belt) is thrust over the Gateway formation (youngest Belt). The actual stratigraphic displacement appears to be greater here than at any other place along the fault trace. The actual vertical displacement here reaches through at least 35,000 feet of Belt series alone, as well as 10,000 feet of interbedded basic sills in the Aldridge-Prichard and Creston-Ravalli formations and an unknown thickness of Purcell lavas interleaved with the Siyeh formation. As one goes southward to Moyie Lakes, the stratigraphic displacement becomes progressively less.

South of Cranbrook the Aldridge-Prichard is thrust over the Siyeh formation and the interbedded Purcell lavas which are on the plunging noses of the anticlinal arch.

Just north of Moyie Lakes the Aldridge-Prichard formation is thrust over the Kitchener-Newland formation, where it is also exposed on the northward plunging nose of the arch.

West of Moyie Lakes the Aldridge-Prichard is thrust over the Creston-Ravalli formation which lies along the west flank of the arch. The stratigraphic displacement from this point southward for about 37 miles remains essentially the same and represents the section of the overthrust with the least apparent displacement. Here it may be as low as 15,000 feet.

South of the Canadian boundary the arch plunges rapidly to the south, and the Aldridge-Prichard to the west of the fault is again thrust over successively higher formations on the east. Along the Moyie River the Aldridge-Prichard almost overlaps the base of the Creston-Ravalli, at the boundary line; but 17 miles farther south it overlaps the top of the formation, thus showing an increase in the stratigraphic interval of nearly 5,000 feet.

Just north of Kootenai River in Idaho the Aldridge-Prichard is thrust over the bottom member of the Kitchener-Newland. At a point 19 miles farther south the Aldridge-Prichard overrides the top member of the Kitchener-Newland. An additional increase of 4,500 feet in the stratigraphic interval is thus noted in this formation.

South of Kootenai River in Montana the Aldridge-Prichard formation is thrust over Striped Peak formation. The stratigraphic throw just south of Troy, Montana, may be as great as that east of Cranbrook, British Columbia.

West of the fault, southwest of Troy, the Aldridge-Prichard dips under the overlying Creston-Ravalli, and at a point about 12 miles south of Troy the Creston-Ravalli is thrust over the Striped Peak, and near Bull Lake it is thrust over a cupola or stock of Mesozoic granite.

Along the west branch of the fault the Creston-Ravalli, on the west side, is thrust over the still younger Kitchener-Newland on the east, which is in turn thrust over the Striped Peak and later beds which may be equivalent to Gateway.

The apparent stratigraphic displacement at the Kootenay River in British Columbia and the Kootenai River in Montana is at least 20,000 feet more than at a point midway along the fault. This may be due to the plunging arch on the east side of the fault. It also may be partly due to erosion on the overthrust lip. Where the stratigraphic throw is least, the fault plane is steeper and approaches verticality. Where the throw is greatest, the plane dips as low as 45° to the west. Where the fault plane is now steep, erosion may have been less than in areas where the plane is more inclined. Subsequent erosion at places where the plane is steep will bare younger formations now east of the fau't and show a greater apparent stratigraphic break. The plane may also flatten with depth, and thus the amount of horizontal displacement is conjectural. At no place is it certain that the horizontal overthrust exceeds the vertical displacement.

To the west of the fault the extremely competent Aldridge-Prichard, which, with its included sills, averages 20,000 feet in thickness, dips in a great monoclinal block easterly or northeasterly to the fault trace at angles of 40°–60°. Just south of Cranbrook this formation dips northward toward a synclinal basin. The Creston-Ravalli formation west of the fault overlies the Aldridge-Prichard and also dips to the east and toward the fault trace.

The formations east of the fault dip quaquaversally away from the arch. Thus to the north they dip north and northwest to the fault trace; on the west they dip northwest, west, and southwest; and on the southwest they dip southwest to the fault trace. On the map it can be seen that not only the strata but also the strikes, dips, and structure are vastly different on opposite sides of the fault.

The effect on the displacement of the injected igneous bodies is

added proof of the overthrust character of the fault. The pattern of the granite cupola south of Troy could be produced only by an overthrust from the west.

THE AGE OF THE THRUST

The only age criterion which can be used is the granite stock or cupola which is cut by the fault. This has been assumed to be an outlying cupola of the Idaho, Selkirk, or Nelson batholiths, which may be one or more batholiths of the same age. The writer[1] suggested a "Mesozoic (Cretaceous?)" age for this granite in 1926, and a Jurassic age for the Nelson and Idaho batholiths in 1927.[2] Ross,[3] in 1928, after a careful study, concluded that a Jurassic age is probable for the Idaho batholith. Lindgren[4] in early papers assigned a Cretaceous age to the Idaho batholith.

Whether the granite is Jurassic or Cretaceous, the fault is definitely post-granite, and pre-Pleistocene. All the faults in the nearby region are younger than the folding which Schofield[5] considers to have occurred in Jurassic time. Schofield says, on page 95, "The faults,[6] are genetically associated with intrusions of granite which is correlated with the Nelson granite of West Kootenay. The age of the Nelson granite is considered to be Jurassic." Schofield[7] thus considers the Moyie fault to be Jurassic in age.

The Bannock and other great overthrust faults which bound the Rocky Mountains farther south are shown by Mansfield[8] and the writer[9] to be younger than Jurassic because Cretaceous beds are

[1] See *Idaho Bur. of Mines and Geol. Bull. 10.*

[2] Virgil R. D. Kirkham, "Groundwater for Municipal Supply at Potlatch, Idaho," *Idaho Bur. of Mines and Geol., Pamphlet 23*, p. 4 (June, 1927).

[3] Clyde P. Ross, "Mesozoic and Tertiary Granitic Rocks in Idaho," *Jour. Geol.*, Vol. XXXVI, No. 8, pp. 637–93.

[4] Waldemar Lindgren, "A Geological Reconnaissance across the Bitterroot and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Survey Prof. Paper 27* (1904), p. 20; "The Gold Belt of the Blue Mountains of Oregon," *U.S. Geol. Survey 22, Amer. Rept.*, Part II (1901), pp. 551–776; *U.S. Geol. Survey, Geologic Atlas of the U.S., Folio No. 104* (1904).

[5] *Op. cit.*

[6] This includes the Moyie fault.

[7] *Op. cit.* [8] *Op. cit.*

[9] See *Idaho Bur. of Mines and Geol. Bull. 8, Pamphlet 19.*

affected. These faults are also known to be older than the Wasatch formation (Eocene).

Consideration of the major structural features of the Rocky Mountains in Idaho and Montana in light of the diastrophic wedge theory of Chamberlin[1] makes it seem entirely likely that the Moyie-Lenia overthrust and other northern Rocky Mountain overthrusts may have been formed at approximately the same time as those in southern Idaho and in southern Montana.

[1] Rollin T. Chamberlin, "The Wedge Theory of Diastrophism," *Jour. Geol.*, Vol. XXXIII (1925), pp. 755–92.

REVIEWS

Sedimentary Petrography. Second edition, complete and revised. By H. B. MILNER. London: Thos. Murby and Co. (D. Van Nostrand), 1929. Pp. 514; figs. 181. $8.00.

This book includes the subject matter of two earlier works, *Introduction to Sedimentary Petrography* (1922) and the *Supplement* (1926), by the same author. Both have been subject to much revision and a wealth of new material has been included in the second edition. This is shown by the fact that the new volume contains almost double the number of pages of the earlier works combined.

Chapters i, ii, and iii are devoted to a brief review of the history of the study of the sedimentary rocks, the collection and storage of samples, and to general laboratory technique.

Chapters iv and v are new. Chapter iv is a summary review of the technique of microscope examination as applied to the detrital minerals. It is much too brief to be a manual of procedure, but references to more elaborate works are given. Chapter v is a brief résumé of quantitative methods of study of the sediments. Shapes of pebbles, mechanical analysis, porosity, specific gravity, and similar topics are summarized with a view to their quantitative determination. As in chapter iv, the reader is referred to the original papers for details of procedure. The inclusion of this chapter, however, is amply justified since it calls attention to quantitative methods and to the real need of quantitative data.

Chapter vi, the largest and probably the most valuable portion of the book, is the compilation of the diagnostic properties of the detrital minerals. In this chapter are included most of the data heretofore published, amended and brought up to date. The tabulation of the optical properties is considerably more complete than that given in the earlier works.

Chapter vii, on consolidated rocks, is the greatest departure from the first edition and *Supplement*. The rocks are classified, following in the main general usage, and each type is taken up in detail, particular emphasis being placed on the petrographic features visible in thin section. The descriptions are supplemented by well-executed plates of microphotographs. On the whole, this chapter has been very well done and is

a very commendable addition. The author has omitted any consideration of the pyroclastic rocks, since he holds the view that their study is impossible "without collateral description of volcanic igneous types." The reviewer does not concur in this opinion. The author has, however, seen fit to include "volcanic clay" or "chemically altered glassy, volcanic ash or tuff." Since both ash and tuff are commingled with normal sediments and are also an important element in some sections and significant in certain instances in correlation, a description of their salient petrographic features would certainly be in order. Rather unusual is the amount of space given to the petrography of peat, lignite, coal and anthracite, cannel and torbanite, oil shale, and to asphalt and asphaltic impregnations. Likewise, an unusual amount of space is devoted to the petrography of salt, gypsum, and other salines.

Chapters viii and ix are devoted to the principles of correlation by petrographic means and to a review of a number of illustrative examples.

In chapter x, the author describes the bearing of the petrographic studies of sediments on the problems of paleogeography. The genetic significance of the detrital minerals is summarized.

Chapter xi, "The Study of Soils," is new. In the writer's own words, the purpose of the chapter is to show that all deposits "lying above the solid rock zone are worthy of the same careful attention as is accorded the more familiar strata." Certainly the distinction between sedentary and transported soils and an understanding of the relationship of particular soils to local geological conditions and to the parent-rock would be a valuable asset to any geologist working in regions of heavy soil cover.

The volume has three Appendixes. The first is the mineral determination tables and the third is a bibliography of about 300 titles. The second is a note on minerals as yet not reported from sediments but which may be found.

The book is well illustrated, especially so when one considers how difficult it is to figure mineral grains. The text is well annotated.

The increasing importance of the polarizing microscope as a means of study of the sediments makes this book a manual which no student of sediments, whether his aims be economic or scientific, can afford to be without. The author of the book makes it clear, however, that the methods therein set forth are not an end in themselves but are means to a better understanding and solution of some of the fundamental problems in sedimentation.

F. J. P.

The Mother Lode System of California. By ADOLPH KNOPF. *Professional Paper 157.* Washington: United States Geological Survey, 1929. Pp. viii+88; figs. 26; pls. 12; one colored geologic map.

This report is the result of two field seasons spent in detailed study. After a consideration of the topography, climate, and gold production, and a historical sketch of the district, the origin and development of the Mother Lode concept is traced from the early idea of a single great persistent quartz vein to the knowledge that the belt is made up of many parallel but interrupted quartz-filled fissures. The general geology is treated briefly, but adequately, and is so well known as to require no comment here.

The larger part of the report deals with the description and origin of the gold deposits which are classified into two main groups: (1) quartz veins and (2) ore bodies of mineralized wall rock. This second group has as many subgroups as there are varieties of wall rock, although the most important from the economic viewpoint is the mineralized greenstone or "gray ore."

The quartz veins are tabular masses dipping steeply eastward and striking between north and northwest. They cut across the structure of the wall rock in both strike and dip, the average divergence being between 15° and 20°.

The quartz filling is not continuous but consists of lenticular masses of coarse, milk-white quartz connected by altered country rock, penetrated by a large number of more or less parallel quartz veinlets. Inclusions of slate and greenstone in the quartz are common and are without exception sharply angular, even those of microscopic size. Inclusions may locally be so abundant that they constitute an angular rubble cemented by quartz.

The ore is localized in shoots which are generally short—200–300 feet is an average given—but usually persist to considerable depths; one has been followed in excess of 5,000 feet on the dip. The hypothesis advanced to account for them is that these shoots or chimneys occupy the paths of active upward movement of the mineral-laden waters. Loss of temperature and hydrostatic head would favor deposition as the waters rose. The parts of the vein not ore shoots are regarded as having been filled by relatively stagnant water. To replenish the gold deposited from such solutions, gold would move in by diffusion, a very notably slower process than the circulation of the thermal waters in the main conduits. Less gold would therefore be deposited in those sections where the circulation was sluggish.

As stated above, the most important ore bodies of mineralized country rock are those made up of mineralized greenstones. Such bodies are composed largely of fine-grained ankerite, with more or less sericite, albite, and quartz and 3 or 4 per cent of pyrite and arsenopyrite.

To Knopf the most remarkable feature of the wall-rock alteration in the region has been the displacement of silica by carbon dioxide. The silica liberated was more than sufficient to furnish the quartz in the veins, and he thinks it unnecessary to appeal to a magma as the source of the silica. He believes that the gold, silver, and other heavy metals, also potassium, arsenic, sulphur, and carbon dioxide, were carried by hot waters. The carbon dioxide liberated immense quantities of silica from the wall rocks, and this silica went into the vein channels, where it was in part deposited as quartz. Why the gold in some places migrated freely into the wall rocks, forming ore bodies of mineralized country rock, and in other places remained in the vein is not decided. Although Knopf thinks that the above-named constituents and heat came from a magma, he believes that the water was largely meteoric.

As to the general conditions of genesis the following quotations are significant:

> The hypothesis that the quartz veins are frozen magmatic injections—dikes, in short, or vein-dikes, as Spurr calls them—is believed to be improbable because, first, the quartz veins nowhere show any evidence of the chilling in the form of fine-grained border facies, even if only narrow, that should be found in dikes that were injected into rocks relatively so cold as those of the Mother Lode belt; and, second, the enormous amount of replacement effected in the wall rocks is out of all proportion to the size of the veins and points to the long-continued flow of solutions through the fissures.
>
> The relative importance of cavity filling, replacement, and the force of crystallization as factors in forming the quartz veins is an unsolved problem. The positive evidence favors the predominance of cavity filling. Nevertheless the gross effect of the appearance of certain veins as viewed in the stopes or crosscuts is that they are the results of replacement. This strong suggestion of replacement origin is well shown by the quartz ore of some of the stopes in the Argonaut mine, which suggests quartz containing innumerable residuals of unreplaced slate. But the evidence as seen under the microscope is firmly against the idea of replacement of the slate by quartz.

In the last thirty-six pages the geology of some thirty individual mines is described in detail following down the lode from north to south.

The report is prefaced by a two-page outline.

B. C. FREEMAN

Brachiopoda Generum et Genotyporum Index et Bibliographia. By CHARLES SCHUCHERT and CLARA LE VENE. *Fossilium Catalogus 1: Animalia*, Pars 42. Berlin: W. Junk, 1929. Pp. 140.

Hall and Clarke, in 1895, recognized in their famous *Handbook* 325 valid brachiopod genera; Schuchert's revision of the Brachiopoda for the second edition of the Zittel-Eastman *Textbook of Paleontology*, in 1913, included 450 generic names; and in the catalogue here reviewed 702 genera and subgenera are considered well established. In spite of this rapid increase in brachiopod genera, it seems clear that eventually many more phylogenetic lines will be recognized. Nevertheless, most paleontologists will fervently agree with Schuchert that "some workers appear to be taking the matter of godfathership too easily with a consequence that many a genus has been brought to the baptismal font that had far better been left unchristened."

Schuchert and Le Vene have carefully considered 895 brachiopod names in preparing their bibliography. Of these 101 are synonyms, 47 are homonyms, 26 are incertae sedis, a few are hypothetic genera, nomina nuda, or other rejecta, and 702 are valid generic names. Of these 702 genera, 5 belong to the order Paleotremata, 44 to the Atremata, 47 to the Neotremata, 189 to the Protremata, and 417 to the Teleotremata. Included in the order Protremata are 44 genera of the superfamily Orthacea, 8 of Clitambonacea, 26 of Pentameracea, 108 of Strophomenacea, and 3 of an unnamed superfamily of unknown relationships. Of the 417 Teleotrematan genera, 100 belong to the Rhynchonellacea, 20 to the Atrypacea, 66 to the Spiriferacea, 55 to the Rostrospiracea, and 176 to the Terebratulacea. The Paleozoic genera number 456, the Mesozoic 177, and the Cenozoic 74.

Although the value of this publication as an index and bibliography scarcely can be overstated, its most significant feature is the new classification of the Brachiopoda proposed by the senior author. In this classification 3 new superfamilies, 7 new families, and 21 new subfamilies are used. The subclasses Gastrocaulia and Pygocaulia, proposed by Thomson[1] in 1927, are not recognized, and although Thomson's order Paleotremata has been adopted, Schuchert includes in it the superfamily Paterinacea, which Thomson placed with the Neotremata. Schuchert correctly credits the subfamily Platidiinae, proposed as new by Thomson in 1927, to Dall, who used the term as early as 1870. Schuchert himself, however,

[1] J. Allan Thomson, *Brachiopod Morphology and Genera*, New Zealand Board of Science and Art, Manual 7 (1927).

proposes as new the superfamily Paterinacea, which Thomson established in 1927 (though the Paterinacea of Schuchert and that of Thomson apparently are not quite one and the same).

In view of the wide acceptance which Schuchert's new classification of the Brachiopoda is certain to enjoy, it perhaps would have been better had he given the reasons for some of his alterations of Thomson's classification. Particularly is this true since in Schuchert's recent[1] review of Thomson's publication he says, "the reviewer sees no need for the new order Paleotremata" (which nevertheless he adopts), and "he agrees . . . . that the superfamilies Rustellacea and Kutorginacea should be removed from the Atremata . . . . and he would refer them . . . . to the order Protremata" (but he actually places them with the Paleotremata). In spite of these changes of mind in the short period of less than a year, the new classification of the Brachiopoda certainly represents a great improvement on all the earlier attempts to classify them.

Schuchert and Le Vene are to be heartily congratulated on the preparation of a reference work which will be of such universal use to paleontologists. The publication is clearly printed, and, as it is completely indexed, it is easy to use.

CAREY CRONEIS

American Mesozoic Mammalia. By GEORGE GAYLORD SIMPSON. *Memoirs of the Peabody Museum of Yale University*, Vol. III, Part I (1929). Pp. xi+171; pls. 32.

"This publication marks the completion of a series of studies which includes all the Mezosoic mammals now known." These forms, which give us our only information as to the early history of the mammals, are of great interest to all students of the vertebrates. Some four decades ago our knowledge of them was summarized by Marsh and by Osborn. But little new material has been discovered since that time, apart from an interesting find of Cretaceous placentals in Mongolia, and it seemed that the subject was an exhausted one. Simpson's work of the last five years, culminating in the present volume and a companion one on the European forms recently published by the British Museum, shows that this was not the case. It is an illustration of what may be done in an apparently reaped field by a competent worker using modern modes of attack.

[1] Charles Schuchert, Review of J. Allan Thomson, *Brachiopod Morphology and Genera*, *Amer. Jour. Sci.*, XV (1928), 526–27.

Among the conclusions reached in this and earlier articles by Simpson are the following: (1) The tiny jaws from the Triassic of North Carolina, usually supposed to be those of primitive mammals, really belong to cynodont reptiles. (2) The multituberculates are neither marsupials nor monotremes, but are to be regarded as a separate subclass of mammals, which probably arose independently from the mammal-like reptile stock. (3) The triconodonts do not illustrate a stage in the development of higher mammals, but are widely removed, phylogenetically, from these forms. (4) Further, triconodonts are not a natural order, part of the types once included in the group (symmetrodonts) being more closely related to the main mammalian stem. (5) Placentals, known a few years ago only in the Tertiary, were present in the Cretaceous both in Mongolia and in North America.

The major portion of the volume is concerned with the morphology and taxonomy of the American forms. In addition to numerous text figures there is an excellent series of stereoscopic microphotographs. The closing chapters discuss the faunal succession, distribution, and phylogeny of the Mesozoic mammals in general.

A. S. R.

Müller-Pouillets Lehrbuch der Physik. Band V, Part I: *Physik der Erde.* Braunschweig: Friedrich Vieweg & Sohn, 1928. Pp. 840; figs. 341; pls. 7. M. 49 paper; M. 53 bound.

This volume on the physics of the earth is just one unit of a general series of textbooks covering the whole field of physics. Many authors have collaborated. The individual chapters are as follows: (i) "Meteorology," by H. V. Ficker; (ii) "Acoustics of the Atmosphere," by Alfred Wegener; (iii) "Optics of the Atmosphere," by Wegener; (iv) "Physics of the Sea," by H. Thorade; (v) "Physics of Glaciers," by H. Hess; (vi) "Earth Magnetism," by A. Nippoldt; (vii) "The Aurora," by G. Angenheister; (viii) "Atmospheric Electricity," by H. Benndorf and V. F. Hess; and (ix) "Mechanics and Thermodynamics of the Body of the Earth," by B. Gutenberg and E. Wiechert.

Much information of value to the geologist is contained in these chapters, though the treatment is naturally more from the physical than from the geological point of view. In many respects it is a great advantage to the geologist to be able to view his problems from the physico-mathematical side. On the other hand, many geological problems have too many variable factors and are consequently too complicated for mathematical

treatment. A general tendency of the mathematical physicist is therefore to ignore many factors in order to bring a problem within the reach of mathematical equations. So commonly the assumptions are so much at variance with the actual phenomena that the conclusions are misleading and do more harm than good. Where they touch his field, the geologist should not take too seriously mathematical deductions that are not based upon a thorough, incisive geological analysis of the natural phenomena.

R. T. C.

"An Experimental Study of Varve Deposition." By H. J. FRASER. *Trans. Royal Soc. of Canada*, XXIII, Sec. 4 (1929), 49–60.

Several years ago W. A. Johnston (*Amer. Jour. Sci.*, Vol. IV [1922], pp. 376–86) studied the modern deposition of varved glacial clay in Lake Louise, Alberta; later Antevs (*Geol. Survey of Canada, Mem. 146* [1925], pp. 23–44; *Bull. Geol. Soc. Amer.*, Vol. XXXVI [1925], pp. 171–72) discussed the physical conditions essential for formation; and now Fraser presents laboratory experiments to determine the relative values of some of the factors affecting the formation of this clay.

Fraser finds that the velocity of fall of particles smaller than 0.5 millimeter in diameter decreases with sinking temperature until a minimum is reached at 0° C. This is what was to be expected, since, with a temperature fall from 4° to 0° C., the increase in the viscosity of the water should overbalance the decrease in the density of the water. As the size of a particle decreases, the retardation of its velocity of fall by lowering temperature becomes greater. This gives rise to the definite grading seen in varved deposits. Thus distinct varves were produced in the laboratory, when unflocculated varved clay was permitted to settle in fresh water just above freezing; whereas only faint lamination developed when unflocculated clay was sedimented in fresh water of 20° C. temperature. Other experiments show that the maximum salinity permitting the formation of varves of coarse clay seems to be about 1/50 that of normal sea-water. At a salinity of more than 1/8 that of normal sea-water a practically massive clay was formed.

Johnston's, Antevs', and Fraser's results agree in all important points; and, in so far as E. M. Kindle's (*Jour. Geol.*, Vol. XXXVIII [1930], pp. 81–87) recent study covers the subject, it corroborates these conclusions.

ERNST ANTEVS

Rutley: Elements of Mineralogy. Twenty-second edition. Revised by H. H. READ. New York: D. van Nostrand Co., 1929. Pp. 394; figs. 84. $2.50.

Dana's Manual of Mineralogy. Fourteenth edition. By W. E. FORD. New York: John Wiley & Sons, 1929. Pp. 476; figs. 360; pls. 10. $4.00.

These two venerable works, the former English, the latter American, are little changed from the previous editions except in the bringing of mineral statistics down to a later date. In addition to doing this, Professor Ford has added a short section describing advances in crystallography from X-ray study and has made a number of minor changes.

Rutley's book leans distinctly toward the economic side; the minerals are classified by their chief metal component, except for silicates, which are arranged according to optical properties. Dana retains in unchanged form its earlier classification on the basis of the negative radical, with the silicates subdivided according to the so-called silicic acids. Rutley is the shorter of the two as it lacks determinative tables and is less thoroughly illustrated. It is interesting to note that in a surprisingly large number of cases the English and Americans use different names for the same mineral species; it is to be hoped that these will be adjusted in the not-too-distant future by an international committee.

Dana omits glauconite and bytownite, gives old formulas for tetrahedrite and enargite, and in general is little changed. Since the determinative tables are unchanged, the student will continue to have difficulty in running down opal, chalcedony, "gel" magnesite, strontianite, calcite of the Mexican onyx variety, powdery kaolinite, and the clay ironstone form of siderite.

D. J. FISHER

Report III of the Federal Oil Conservation Board: Washington, D. C.; Government Printing Office, 1929. Pp. 218. 30 cents (Superintendent of Documents).

This is a progress report, of interest to geologists mainly because of Appendix C, "Petroleum Resources of Foreign Countries and Outlying Possessions of the United States," by A. H. Redfield. This fills the major portion of the booklet, and, besides covering in brief but worth-while fashion the developments in petroleum exploration outside of the United

States proper, contains extensive bibliographies on the countries concerned. It should be in the library of every geologist and economist interested in petroleum.

D. J. F.

Map of the Coal Fields of Pennsylvania. Compiled by J. D. SISLER. Pennsylvania Topog. and Geol. Survey, 1929.

The map, which shows the whole state on a scale of 6 miles to the inch, has colors to distinguish the various Pennsylvanian formations (Pottsville, Allegheny, Conemaugh, and Monongahela), the Dunkard, and the post-Pottsville anthracite beds. Originally intended as Plate II of Part I of Volume I of Bulletin M-6, *Bituminous Coal Fields of Pennsylvania*, it is designated as Plate I of Part II of this bulletin.

D. J. F.

Bulletin of the Geological Survey of China No. 10 (1928). Pp. 42; pls. 14.

This *Bulletin* contains three articles by Chinese geologists. The first is "Geology of the Ta Ching Shan Range and Its Coal Fields" by C. C. Wang, who summarizes the tectonic and physiographic history as follows: Cretaceous lateral compression, folding, and thrusting; Tertiary erosion to maturity, Tanghsien stage; Quaternary Tachingshan fault and uplift, followed by erosion, Fenho stage; Late Quaternary or recent revival of uplift and erosion, Huaugho stage. A map is appended.

The second article is a short summary of the topography and stratigraphy of Hsuan Hua, Cho Lu, and Huai Lai districts of northwestern Chihli. The third article is longer and discusses the ancient volcanoes of Hsuan-Hua. The author is H. S. Wang. He gives petrographic descriptions of the various eruptive rocks, and concludes that they were the deposits of a more or less continuous eruption through the Jurassic and part of the Cretaceous.

C. C. B.